Implications of volcanism in coastal California for the Neogene deformation history of western North America

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[1] The geologic record of coastal California includes evidence of numerous volcanic centers younger than 30 Ma that do not appear to have erupted in an arc setting. By correlating these volcanic centers with specific slab windows predicted from analysis of magnetic anomalies on the Pacific plate, we add new constraints to tectonic reconstructions since 30 Ma. Our correlations, such as erupting the Morro Rock–Islay Hill complex south of the Pioneer fracture zone and the Iversen Basalt south of the Mendocino fracture zone, require larger displacements within western North America than advocated by most previous authors. Specifically, we infer at least 315 km of motion between the Sierra Nevada and rigid North America at an azimuth of about N60°W and at least 515 km between Baja California and rigid North America in a similar direction. A consequence of inferring a large displacement of Baja California is that the Pacific–North American plate boundary must have developed most of its current form prior to 10 Ma. We interpret a slab window developing between Cocos and Monterey plates after 19 Ma that reconstructs under nearly all of the southern California volcanic centers dated at 18–14 Ma. Most of the sedimentary basins associated with volcanic rocks show brief periods of rapid subsidence synchronous with volcanism, followed by slow subsidence of variable but often extended duration, consistent with rapid extension of cold lithosphere over recently introduced hot asthenosphere. **Citation:** Wilson, D. S., P. A. McCrory, and R. G. Stanley (2005), Implications of volcanism in coastal California for the Neogene deformation history of western North America, *Tectonics*, *24*, TC3008, doi:10.1029/2003TC001621.

1. Introduction

[2] The relationship of the tectonics of western North America to the seafloor spreading history recorded on the adjacent Pacific plate is a topic that has received great interest since the pioneering work of *Atwater* [1970]. A very useful aspect of the continuing study of this topic has been calculating the relative positions of the Pacific and North American plates by summing North America-Africa, Africa-Antarctica, and Antarctica-Pacific relative motion [*Atwater and Molnar*, 1973; *Stock and Molnar*, 1988; *Atwater and Stock*, 1998]. One limitation of these calculations is the lack of redundant information that would reveal departures from the assumption of rigid plates or other biases that would cause inaccuracies.

[3] One possible way of checking the plate circuit involves using the volcanic record in the area of Pacific-North America interaction. *Fox et al.* [1985] demonstrated a northward progression of volcanism in the California Coast Ranges that correlates with the northward motion of the Mendocino triple junction since 15 Ma. Volcanism is expected in this setting because the edge of the subducted slab aligning with the Mendocino fracture zone has a northward component of motion, and mantle must well up behind the slab edge [*Lachenbruch and Sass*, 1980; *Zandt and Furlong*, 1982]. Older than 15 Ma, the volcanic pattern is more complicated than simple northward progression [*Stanley*, 1987], involving several pulses in localized areas that have subsequently been dispersed by fault offsets. *Sharma et al.* [1991] were among the first to suggest that these older volcanic rocks correlate to slab windows as the earliest spreading center segments of the East Pacific Rise encountered the subduction zone, and that interpretation has been expanded by *Cole and Basu* [1995] and *Dickinson* [1997].

[4] We contend that many of the coastal volcanic rocks can be correlated to specific slab windows predicted by the offshore seafloor spreading record. These correlations allow new tests of reconstruction models which include components of global plate circuit, North American deformation, and timescale calibration, all three of which are uncertain. We define our model for North American deformation more rigorously than in previous studies by specifying finite rotations of numerous fault blocks, using the same mathematical description as motions of the major plates. In some cases our results show slight inconsistencies between generally accepted aspects of the previous reconstruction models, and we outline the possible range of adjustments to the reconstructions or the timescale that eliminate the inconsistency. In the case of the position of Baja California prior to 10 Ma, we find that the widely accepted interpretation of only 300 km of total motion with respect to North America

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conflicts with both the volcanic record and other accepted geologic constraints on the reconstructions. Additionally, we find that our new reconstruction offers several insights into the geologic processes involved in volcanism in generally extensional settings near the continental margin.

2. Volcanic Record

[5] Our interpretation of the volcanic record of coastal California builds on that of numerous authors, and closely follows the review of *Dickinson* [1997]. He divided these volcanic rocks into three age and geographic groups, namely, a mid-Tertiary group with ages 27–22 Ma located primarily in central California; a mid-Miocene group with ages 18–12 Ma primarily in southern California; and a post-mid-Miocene group with ages younger than 15 Ma showing a northward younging age progression through central and northern California. Our compilation of well-determined ages (Table 1 and Figure 1, simplified from *Stanley et al.* [2000]) includes numerous recently published dates not available for previous compilations. We find it useful to subdivide Dickinson's mid-Tertiary group into an older group with ages 27–25 Ma that occurs within and slightly north of the Transverse Ranges, and a younger group with ages 24–22 Ma that extends well to the north. We limit this compilation to units older than 12 Ma because younger units offer few constraints for choosing among alternative large-scale reconstructions. This age restriction excludes most of the post-mid-Miocene group; their ages and paleogeographic significance have been recently reviewed by *Wakabayashi* [1999]. Most of the units are radiometrically dated, but we include units that were dated by other means, for example, on the basis of biostratigraphic analysis of associated sedimentary strata, where the control is adequate for assignment to one of our age groups. In general, we report a single location judged to be as close as possible to the eruptive center, even for units with substantial outcrop area.

[6] Numerous authors, including fairly recently *Lonsdale* [1991] and *Tennyson* [1989], have attributed older members of the coastal volcanic province to a subduction zone setting. This interpretation, however, is not supported by geochemical analyses. As reviewed by *Gill* [1981], distinguishing characteristics of arc volcanic rocks include depletion of high-field-strength elements Ti, Zr, Hf, Nb, and Ta. These depletions are typically recognized by ratios of the more incompatible elements Ta and Nb to comparably incompatible large-ion lithophile elements such as Ba, Th, and La, e.g., La/Ta > 30, La/Nb > 2, and Ba/Ta > 450. Also, arc volcanic rocks generally have $^{87}Sr/^{86}Sr > 0.7030$, though this ratio is only distinctive relative to lavas from very depleted sources such as mid-ocean ridges away from hot spots. Generalizing results from the well-studied coastal volcanic units within the Tecuya Formation [*Sharma et al.*, 1991], the Santa Maria basin [*Cole and Basu*, 1992], the Conejo Volcanics [*Hurst*, 1982; *Weigand and Savage*, 1993], and regional overviews [*Johnson and O'Neil*, 1984; *Cole and Basu*, 1995], these units generally show a range of compositions, spanning basalt to andesite and sometimes basalt to rhyolite. The basaltic lavas generally show an affinity with mid-ocean ridge basalts and lack diagnostic characteristics of arc lavas, especially depletions in Nb and Ta. *Cole and Basu* [1995] tabulate a range of Ba/Ta ratios of 36–338 for basalts of these suites, substantially overlapping the field for mid-ocean ridge basalts but not overlapping the field diagnostic of continental volcanic arcs. Some of the more silicic units do show Nb and Ta depletions, but correlation of $^{87}Sr/^{86}Sr$ with silica content in these units suggests that the depletions are inherited from assimilated older continental crust. The fraction of continental material in members of the post-mid-Miocene northward migrating group is generally high, as indicated by several lines of evidence including oxygen isotope ratios and Th contents [*Johnson and O'Neil*, 1984; *ten Brink et al.*, 1999].

[7] In two cases elsewhere where the geometry of slab windows can be predicted relative to the continent with much greater confidence, geochemically similar volcanic rocks have been dated to near the time a slab window arrived under the continent. In the area of the northern Antarctic Peninsula, several suites of upper Tertiary alkalic basalts have ages generally a few million years younger than the predicted time of appearance of a slab window between the Antarctic and Phoenix plates [*Hole and Larter*, 1993]. In Patagonia, extensive lava fields can be matched to two specific segments of the Nazca-Antarctic spreading center that started to form slab windows at ~12 Ma and ~6 Ma [*Gorring et al.*, 1997]. Eruptive ages in these fields are progressively younger to the east, and the rate of eastward younging indicates that initial volcanism quickly followed eastward passage of the young edge of the subducted Nazca plate formed by offshore seafloor spreading. These analogies strengthen the case that volcanic centers in coastal California can be used as paleogeographic markers to be correlated with slab windows predicted from analysis of Pacific plate isochrons.

3. Seafloor Spreading Record

[8] Our interpretation of the offshore magnetic anomaly record (Figure 2) builds on that of many previous workers with only moderate refinements. We concentrate on more quantitative prediction of the subducted slab geometry than has been previously attempted, and interpret diffuse boundaries in very young oceanic lithosphere, simplifying the history by using fewer microplates. *Menard* [1978] refined previous interpretations of a single Farallon plate between the Pacific and North American plates for the interval of about 50–30 Myr because of the observation that fracture zones from Pioneer fracture zone (FZ) northward were concentric about a different, closer rotation pole than fracture zones from Murray FZ southward. He termed the northern plate the Vancouver plate, but we prefer to refer to it as the Juan de Fuca plate for reasons of simple precedence. *Lonsdale* [1991] developed the framework for the more complex history after 30 Ma, when additional microplates are needed besides the main Farallon and Juan de Fuca plates. He proposed the existence of two microplates

Table 1. Ages of Volcanic Units

Unit Name or Landmark	Map Symbol	Latitude, °N	Longitude, °W	Age, Ma	Basis for Age	Age Reference
			27-25 Ma Group, Late Oligocene			
Carmel[a]	CA	36.56	121.94	27	K-Ar	*Clark et al.* [1984]
York Mountain[a]	YM1	35.49	120.83	27-25	Field relations	*Seiders* [1982] and *Stanley et al.* [1996]
Morro Rock-Islay Hill	MR	35.32	120.73	27-26	$^{40}Ar/^{39}Ar$	*Turner* [1970] and *Cole and Stanley* [1998]
Pine Creek[a]	PC	35.22	120.32	27-26	K-Ar	*Vedder et al.* [1991]
Wagon Road Canyon[a]	WR	34.71	119.20	25	$^{40}Ar/^{39}Ar$	*Stanley et al.* [2000]
San Gabriel Mountains[a]	SG1	34.26	117.60	26-25	$^{40}Ar/^{39}Ar$, U-Pb	*Nourse et al.* [1998] and *May and Walker* [1989]
Mountain Meadows Dacite	MM	34.10	117.78	28-27	$^{40}Ar/^{39}Ar$	*Nourse et al.* [1998]
			25-20 Ma Group, Late Oligocene to Early Miocene			
Iversen Basalt	IB	38.86	123.65	25-23	K-Ar	*Turner* [1970]
Half Moon Bay[a]	HB	37.47	122.38	25-20	field relations	*Stanley* [1987]
Mindego Basalt	MB	37.33	122.25	>20	K-Ar	*Turner* [1970]
Pescadero Beach[a]	PB	37.27	122.41	22	K-Ar	*Taylor* [1988, 1990]
Zayante Creek[a]	ZC	37.12	122.02	24-23	K-Ar	*Turner* [1970]
Point Año Nuevo[a]	AN	37.11	122.32	25-20	field relations	*Brabb et al.* [1977] and *Clark* [1981]
Gabilan Range[a]	GR	36.82	121.55	23-21	K-Ar	*Turner* [1968] and *Weigand and Thomas* [1990]
Soquel Canyon[a]	SQ	36.80	122.00	24-23	$^{40}Ar/^{39}Ar$	*Stakes et al.* [1998]
Pinnacles Volcanic Formation	PV	36.47	121.18	25-22	K-Ar, $^{40}Ar/^{39}Ar$	*Turner* [1968] and *Weigand and Swisher* [1991]
Simmler Formation	SI	35.18	120.21	23	K-Ar	*Ballance et al.* [1983]
Lopez Mountain[a]	LM1	35.15	120.47	24-22	Field relations	*McLean* [1995]
Tunis Creek[a]	TU	34.97	118.79	23-22	$^{40}Ar/^{39}Ar$	*Plescia et al.* [1994]
Tecuya Formation	TE	34.93	118.98	25-22	K-Ar	*Turner* [1968, 1970]
Plush Ranch Formation	PL	34.78	119.09	27-23	K-Ar	*Frizzell and Weigand* [1993]
Neenach Volcanic Formation	NV	34.75	118.55	24-21	K-Ar, $^{40}Ar/^{39}Ar$	*Matthews* [1973] and *Weigand and Swisher* [1991]
Vasquez Formation	VF	34.47	118.29	26-23	K-Ar	*Crowell* [1973] and *Frizzell and Weigand* [1993]
Diligencia Formation	DF	33.55	115.68	24-21	K-Ar	*Crowell* [1973] and *Frizzell and Weigand* [1993]
			20-12 Ma Group, Southern California Early to Middle Miocene			
York Mountain[a]	YM2	35.49	120.83	<20	Field relations	*Seiders* [1982] and *Stanley et al.* [1996]
NW Caliente Range[a]	NC	35.22	119.95	20-14	Field relations	*Bartow* [1991]
Lopez Mountain[a]	LM2	35.26	120.55	17	K-Ar	*McLean* [1994]
Obispo Formation	OF	35.08	120.77	18-15	K-Ar	*Turner* [1970] and *Stanley et al.* [1996]
Triple Basalts	TB	35.00	119.59	17-14	K-Ar	*Turner* [1970]
Point Sal[a]	PS	34.89	120.64	<17	field relations	*Cole and Stanley* [1998]
Catway Road[a]	CR	34.76	119.98	20-16	K-Ar	*Vedder et al.* [1994] and *Hall* [1981]
Hells Half Acre[a]	HH	34.70	119.88	20-17	K-Ar	*Fritsche and Thomas* [1990]
Santa Rosa Creek[a]	SR	34.61	120.26	18-16	K-Ar	*Turner* [1970]
Tranquillon Volcanics	TM	34.58	120.56	18-17	$^{40}Ar/^{39}Ar$	*Stanley et al.* [1996]
San Gabriel Mountains[a]	SG2	34.20	117.75	19-14	field relations	*Nourse et al.* [1998]
Conejo Volcanics	CV	34.17	118.92	17-14	K-Ar	*Turner and Campbell* [1979]
Cahuenga Pass[a]	CP	34.13	118.38	17-14	field relations	*Eaton* [1957]
Glendora Volcanics	GV	34.10	117.80	17-15	$^{40}Ar/^{39}Ar$	*Nourse et al.* [1998]
Santa Cruz Island Volcanics	SCR	34.03	119.77	17-16	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
San Miguel Island Volcanics	SM	34.03	120.30	19-17	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
Anacapa Island[a]	AC	34.01	119.36	16	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
Zuma Volcanics	ZV	34.00	118.80	17-15	K-Ar	*Berry et al.* [1976]
Inglewood oil field	IO	34.00	118.37	17-14	field relations	*Wright* [1991]
Blanca Formation	BF	33.98	119.73	16	$^{40}Ar/^{39}Ar$	*Weigand et al.* [1998]
Santa Rosa Island Volcanics	SRI	33.95	120.10	19-18	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
West Coyote oil field[a]	WC	33.90	117.98	17-14	field relations	*Blake* [1991] and *Wright* [1991]
Dominguez oil field	DO	33.87	118.24	14-12	field relations	*West et al.* [1988]
Long Beach Airport oil field[a]	LO	33.82	118.16	16-14	field relations	*Wright* [1991]
Palos Verdes Peninsula[a]	PVP	33.75	118.35	17-15	K-Ar	*Turner* [1970] and *Eaton* [1957]
San Joaquin Hills[a]	SJ	33.60	117.80	16-14	K-Ar	*Turner* [1970] and *Eaton* [1957]
Santa Barbara Island Volcanics	SB	33.46	119.04	16-15	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
Santa Catalina Island[a]	STC	33.38	118.42	17	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
San Clemente Island[a]	SCL	32.92	118.55	16-14	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
Jacumba-Vallecitos[a]	JV	32.75	116.09	20-16	K-Ar	*Gastil et al.* [1979]

Table 1. (continued)

Unit Name or Landmark	Map Symbol	Latitude, °N	Longitude, °W	Age, Ma	Basis for Age	Age Reference
Rosarito Beach Formation	RB	32.48	117.10	16-15	$^{40}Ar/^{39}Ar$	*Luyendyk et al.* [1998]
16-12 Ma Group, Northern California Northward Migrating, Oldest Units						
Burdell Mountain[a]	BM	38.13	122.57	13-12	K-Ar, $^{40}Ar/^{39}Ar$	*Mankinen* [1972] and *Wakabayashi* [1999]
Page Mill Basalt	PM	37.40	122.16	16-14	K-Ar, $^{40}Ar/^{39}Ar$	*Turner* [1970] and *Wakabayashi* [1999]
New Almaden[a]	NA	37.24	121.91	16-15	K-Ar	*Nakata et al.* [1993]

[a]Name of nearby landmark. K-Ar ages from pre-1978 references have been recalculated to more recent decay constants using the method of *Dalrymple* [1979]. Age range generally reflects scatter and uncertainty instead of documented duration of activity. Within age groups, values are sorted by latitude.

between the major eastern plates, the Monterey microplate to the north and the Arguello microplate to the south. According to his interpretation, spreading on the Pacific-Monterey ridge axes formed the northeast striking anomalies C9 through C6 at latitudes 35–38°N, and a small fragment of the Monterey plate remains offshore at 35–36°N, captured by the Pacific plate at about 19 Ma.

[9] We model the evolution of slab windows by using finite rotations to predict the positions of the subducted plates by rotating observed isochrons from the Pacific plate. Depending on the time reconstructed, we assume either two or three plates spreading east of the Pacific plate. To predict the age and position of the Juan de Fuca plate near the Pioneer fracture zone, we follow the rotation model of *Wilson* [1988] as closely as possible, though some modifications were necessary as that model was only based on data north of the Mendocino fracture zone. To the south, we derive new finite rotations assuming symmetric, orthogonal spreading to predict the counterparts of Pacific plate anomalies at 28–33°N. For times older than chron C9n, we find it possible to use rotations consistent with Farallon-Pacific motion derived from Pacific and Nazca plate data by *Handschumacher* [1976] and *Pardo-Casas and Molnar* [1987], and for C5E–C5B, our rotations are consistent with those of *Wilson* [1996], derived from Cocos and Pacific plate data. The proper plate nomenclature near 30°N depends on still unanswered questions of plate rigidity; we refer to the eastern plate as the Farallon plate prior to 25 Ma and as the Cocos plate from 25 to 14 Ma. Starting during chron C10n, we also specify a separate Monterey plate. We use anomaly identifications closely following *Lonsdale* [1991], and our finite rotation history uses closer pole locations with more pivoting than the previous quantifications of *Fernandez and Hey* [1991] or *McCrory et al.* [1995]. As described below, these closer pole locations allow interpretations of fewer plates using tectonics analogous to active oceanic microplates including Easter and Juan Fernandez [*Schouten et al.*, 1993]. We were surprised to discover no need for the Monterey-Pacific and Cocos-Pacific rotations to be different for chrons C6B-6.

[10] Figure 3 illustrates our model for the evolution of the slab geometry, using the rotation model from Table 2. Prior to Chron C13, Juan de Fuca-Farallon motion was slow enough that its direction is highly uncertain, and a map restricted to the Pioneer-Murray area shows no evidence for more than two plates (Figure 3a). We interpret the slow relative motion as indicating moderately strong coupling between the Juan de Fuca and Farallon plates, with the deformation occurring in the weakest area as controlled by plate shape and age. For chrons C13–C10, the symmetric spreading assumption implies faster motion of the Juan de Fuca plate than the Farallon plate. Because there is no evidence for a stable transform fault forming at the ridge axis between Pioneer and Murray transforms, we assume the boundary between the two was a diffuse, right-lateral shear zone (Figure 3b).

[11] The reorganization that occurred during chrons C10–C9 left a sufficiently complicated record that some of the timing is not immediately obvious. The oldest

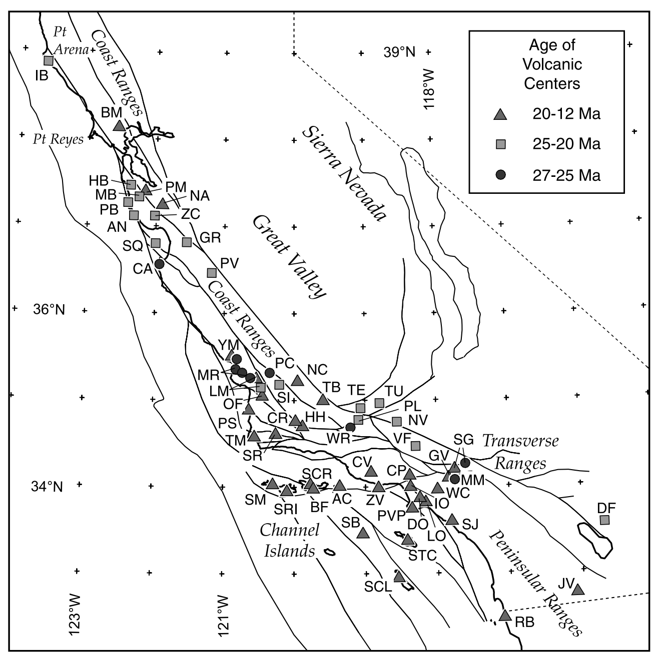

Figure 1. Map showing approximate locations of late Oligocene through middle Miocene volcanic centers in coastal California (modified from *Stanley et al.* [2000]). See Table 1 for explanation of letter symbols.

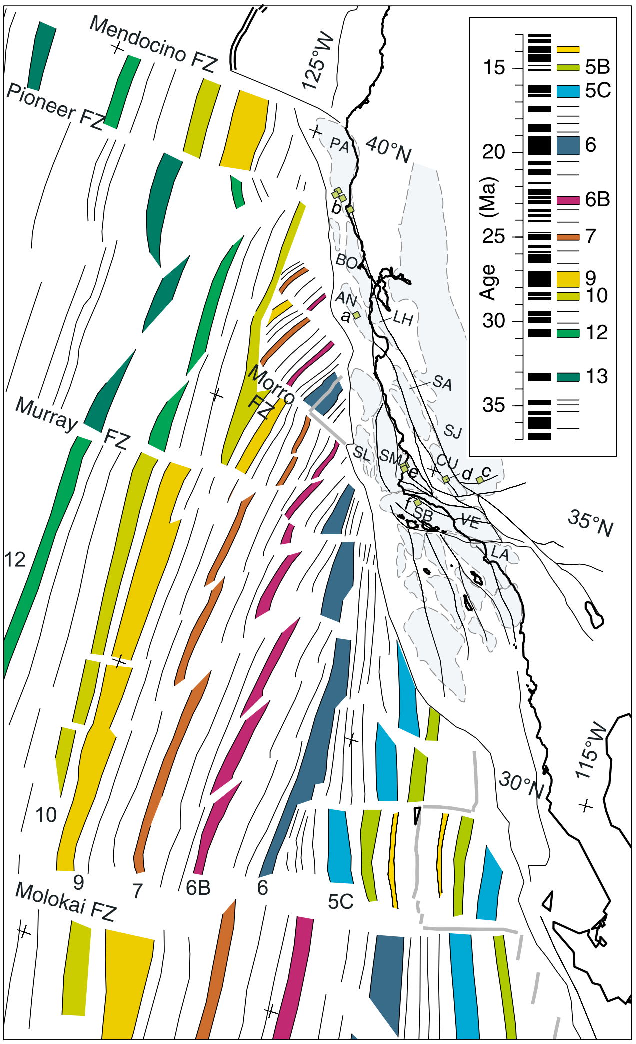

Figure 2. Magnetic anomaly location map, after *Lonsdale* [1991] and *Atwater and Severinghaus* [1989]. Major changes in plate motion are recorded by changes of anomaly strike at 28.5 Ma (C10), though only between Pioneer and Murray fracture zones, and at 19 Ma (C6). Spreading west of Baja California ceased about 12.5 Ma. Anomalies C6B–C6 are approximately radial about a pole near the top right corner. Labeled diamonds denote location of backstrip sites discussed in text (see Figure 9 for explanation of letter symbols). Upper Cenozoic marine sedimentary basins are denoted by shading. PA, Point Arena basin; BO, Bodega or Point Reyes basin; LH, La Honda or Santa Cruz basin; SA, Salinas basin; SL, Santa Lucia basin; SM, Santa Maria basin, offshore and onshore; CU, Cuyama basin; SJ, San Joaquin basin; SB, Santa Barbara basin; VE, Ventura basin; LA, Los Angeles basin.

anomaly unequivocally showing substantial reorientation is C10.1n at 34.5–35.0°N, between the Murray and newly formed Morro fracture zones [*Wilson*, 1988; *Lonsdale*, 1991]. Though only the area north of the Morro fracture zone, where most of C9–C10 is missing, clearly records Monterey-Pacific spreading, we interpret the older part of C10n as the time of initial separation of the Monterey plate. *Wilson* [1988] described counterclockwise change in relative motion for the northern Juan de Fuca-Pacific system during chron C9n, accompanied by a change in spreading rate gradients that implies a change from concave-northward transform faults to concave southward. The change in curvature predicts a clockwise change in motion direction for eastern Mendocino and Pioneer transforms. In the Murray-Molokai corridor to the south, *Lonsdale* [1991] has mapped a clockwise change for C9(y) and younger relative to C9(o) and older. Because neither system north of Pioneer FZ or south of Murray FZ shows changes during C10n but both change clockwise (at least locally) during C9n, we infer that separation of the Monterey plate did not immediately affect the coupling between the Juan de Fuca and Farallon plates. The only way this appears possible is for the Monterey plate to have separated along a break nearly parallel to the subduction zone and not far downdip from it (Figure 3c). We interpret the Monterey plate as pivoting relative to the Farallon plate about a pole on or near their border, similar to that observed for the Easter microplate [*Naar and Hey*, 1991; *Rusby and Searle*, 1995], and discussed generally by *Schouten et al.* [1993]. A diffuse boundary would occupy the area near the eastern trace of the Murray fracture zone, with convergence between the Monterey and Farallon plates (Figures 3c and 3d) resolved by some combination of thrusting and westward extrusion, slowing the spreading rate on the adjacent ridge segment. Our models of isochron positions do not include this complication, instead simply treating isochrons formed north of Murray fracture zone as part of the rigid Pacific and Monterey plates. Shading shows the interpreted boundary zone position.

[12] From 28 to 25 Ma, the change in the slab window geometry is simply a matter of growth as the plate fragments move apart. As pointed out by *Atwater and Stock* [1998], there is little uncertainty about the position of the northern part of this window relative to the Pacific plate. The southern edge of the Juan de Fuca plate must have moved eastward aligned with the Pioneer fracture zone while the Monterey plate moved southeastward. By 25 Ma, the slab window also includes the spreading segment between Mendocino and Pioneer fracture zone (Figure 3e), where anomaly 7A is the oldest preserved offshore. Rapid relative motion of the southern Juan de Fuca plate relative to the Pacific plate implies that this portion of the slab window grew rapidly (Figure 3f). Again, the position of this part of the slab window relative to the Pacific plate is not significantly uncertain.

[13] After 25 Ma (chron C7), the motion between Cocos and Monterey plates required by the symmetric, orthogonal spreading assumption slows significantly, and by 23 Ma (chron C6B), no relative motion is required. The nearshore part of the slab window grows slowly during this time interval as a result of southward motion of the Monterey plate relative to the edge of the Juan de Fuca plate aligned with the Mendocino fracture zone (Figure 3g). Capture of the Monterey plate by the Cocos plate, however, was not

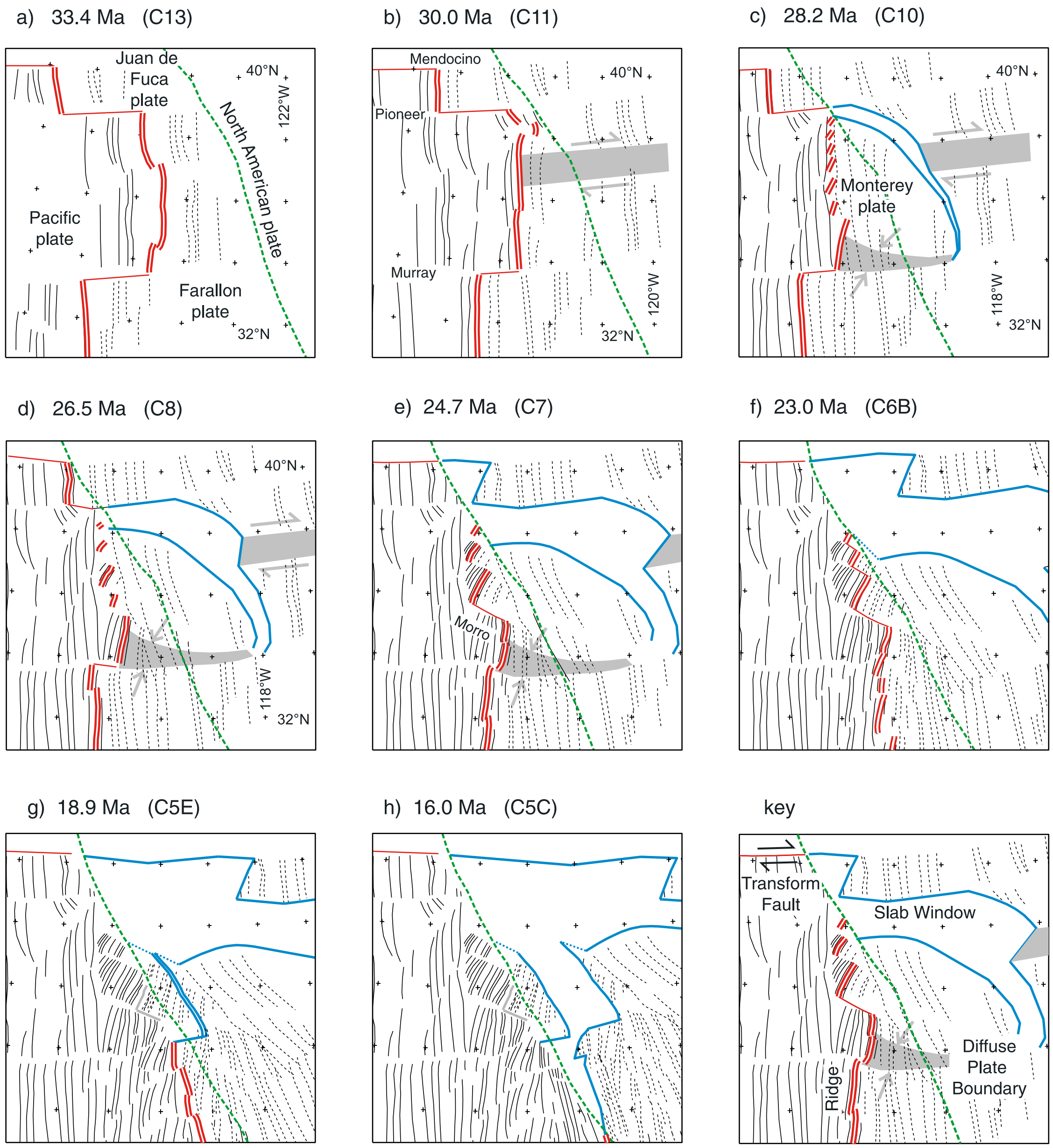

Figure 3. Reconstruction models predicting geometry of oceanic crust east of the Pacific plate, including slab windows beneath North America. Isochron positions on eastern plates (dashed) are predicted by rotating Pacific plate isochrons according to the stage rotation history of Table 2. Approximate position of the North American margin is indicated by the dashed line, and shading with paired relative motion arrows shows presumed diffuse boundaries within oceanic plates. The reference frame is fixed to the Pacific plate, with Figure 3a and 3b frames having more westerly centers than the other frames. (a) Prior to chron C13, Juan de Fuca-Farallon plate motion is slow rotation about a local pivot. (b) As the EPR approaches the subduction zone, faster right-lateral relative motion develops. (c) During chron C10n, the Monterey microplate separates. (d) Both Pacific-Juan de Fuca and Pacific-Farallon relative motion shift clockwise during chron C9n. (e) A separate slab window develops between the Mendocino and Pioneer fracture zones during chron C8. (f) By chron 6B, Cocos-Pacific motion has slowed to the point where a Cocos-Monterey boundary is no longer required. (g) At about chron C6y, Monterey-Pacific spreading stops, and we interpret that the Cocos-Monterey break position was parallel to the continental margin. (h) Continued Cocos-Pacific spreading opens a slab window east of the Monterey plate.

Table 2. Stage Rotation Model for Oceanic Plates[a]

Age, Ma	Latitude, °N	Longitude, °E	Rate, deg/Myr
Farallon/Cocos-Pacific			
37.00	82.5	100.0	0.70
27.90	70.0	−110.0	0.65
25.80	65.0	−110.0	0.69
23.30	42.0	−119.0	1.95
22.00	40.7	−119.7	1.78
19.10	50.0	−125.0	0.94
17.60	52.0	−130.0	0.90
15.50	50.0	−128.0	0.80
Juan de Fuca-Pacific			
37.00	76.5	−144.0	1.02
27.90	47.0	52.0	0.49
25.20	78.0	−156.0	1.00
23.40	25.0	50.0	0.32
18.67	88.0	−70.0	0.42
Monterey-Pacific			
28.60	40.0	−120.0	3.38
25.20	46.0	−116.0	1.41
23.30	42.0	−119.0	1.95
22.00	40.7	−119.7	1.78
19.10	—	—	0.00

[a]Age specifies beginning of time interval for which rotation rate applies. Rate is half rate, positive counterclockwise relative to Pacific plate.

permanent, because spreading ceased north of 35°N during or just after chron C6n [*Lonsdale*, 1991] but continued south of 35°N. Our interpretation is that the onshore volcanic record indicates that the break between the preserved offshore fragment of the Monterey plate and the Cocos plate occurred near the subduction zone (Figure 3g). Details of this interpretation will be presented in the following section. The initial position of the break is not well constrained by the offshore record, but once a position is chosen, the evolution of the subsequent slab window geometry is governed by the well constrained relative motion of the Cocos and Pacific plates.

[14] For simplicity, our reconstructions predict the positions of slabs by rotation of conjugate features from the Pacific plate, without correction for slab dip or thermal erosion. For the most relevant issue of predicting the northern limit of the slab windows delimited by the extensions of the Pioneer and Mendocino fracture zones, the high angle between the fracture zones and the continental margin renders the dip correction unimportant, and the relatively fast convergence rate and moderate slab age for the Juan de Fuca plate imply that expansion of the north edge of the slab window by thermal erosion is probably trivial compared with other uncertainties. Both factors will contribute more significantly to the uncertainty in predicting the rate of eastward expansion of slab windows. Because thermal erosion and slab dip corrections have opposing predictions for the rate of slab window growth, their effects may cancel.

4. Kinematic Reconstruction Model

[15] Our goal is to determine whether correlating the coastal volcanic rocks with the slab windows has any unreasonable implications that would require revising generally accepted ideas about relative motions in the late Cenozoic. To this end, we combine a global circuit of major plate motions, similar to that used by other recent authors, with a new model that describes relative motions within North America using finite rotations on a sphere among large numbers of rigid blocks. Broadly similar reconstructions have recently been attempted [*Nicholson et al.*, 1994; *Bohannon and Parsons*, 1995; *Atwater and Stock*, 1998], but with less rigorous restoration of continental deformation, and generally different priorities driving construction of the model. The main advantage of our technique is that the position of a continental fragment relative to the Pacific plate is an exact prediction of the kinematic model; relative positions of volcanic centers and slab windows can be used as direct tests of a set of relative motion parameters. Furthermore, with all of the reconstruction performed by parameterized modeling, internal consistency of the reconstructions is tested much more rigorously than in reconstructions with a substantial component of freehand drafting.

[16] Our model for North America includes a few major blocks generally recognized as mobile but nearly rigid, namely, the Colorado Plateau, Sierra Nevada-Great Valley, Baja California, and the Sierra Madre Occidental (Figure 4). Close to the coast, especially in the areas where the volcanic rocks are observed, we keep track of many individual blocks bounded by major to moderate faults. For the inland deformation zones, commonly characterized by basin and range extension, we ignore most of the individual faults and fault blocks, considering only the motion between the major blocks and the North America craton. Determining motion between the major blocks by summing displacement across all the faults in an extensional province is a sufficiently difficult problem that it has only been attempted in the relatively narrow Las Vegas-Death Valley corridor [*Wernicke et al.*, 1988; *Snow and Wernicke*, 2000], and we include a few blocks in this corridor to illustrate the general similarities between our reconstructions.

[17] The offsets we restore on major strike-slip faults in California generally are widely accepted, and follow those of *Dickinson* [1996] more than any other single author. Our across-fault correlations include Pinnacles-Neenach across the San Andreas fault [*Matthews*, 1976; *Sims*, 1993], Point Reyes-Carmel across the San Gregorio fault [*Clark et al.*, 1984; *Stakes et al.*, 1998], and subsurface features offset about 40 km across the Reliz-Rinconada system in the Salinas Valley [*Graham*, 1978]. Large rotations in the Transverse Ranges of southern California documented by paleomagnetic results summarized by *Luyendyk et al.* [1985], *Luyendyk* [1991] and *Dickinson* [1996] are also included. Following *Crouch and Suppe* [1993], we restore substantial extension, primarily of middle Miocene age, in the Inner Borderland region offshore from southern California. Many faults have poorly known offsets, and even the best constrained vertical axis rotations are uncertain by about 10°, so constructing a complete model requires numerous subjective judgments. Information on timing of

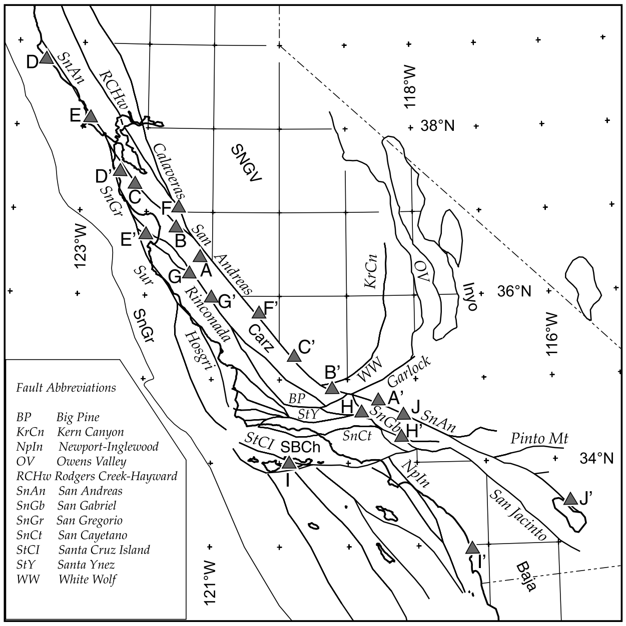

Figure 4. Location map for faults used in the kinematic reconstruction. Labeled triangles show correlation points used to constrain fault offsets: A-A′, Pinnacles-Neenach mid-Tertiary volcanic rocks [*Matthews*, 1976; *Sims*, 1993]; B-B′, multiple Mesozoic basement to early Miocene features, summarized by *Dickinson* [1996]; C-C′, early Miocene paleobathymetry and sedimentary facies [*Graham et al.*, 1989]; D-D′, Cretaceous conglomerate [*Wentworth et al.*, 1998; *Burnham*, 1998]; E-E′, Cretaceous pluton [*Stakes et al.*, 1998]; F-F′, basalts and limestones of the Franciscan Complex [*McLaughlin et al.*, 1996]; G-G′, early Miocene paleobathymetry [*Graham*, 1978]; H-H′, Cretaceous pluton [*Crowell*, 1962]; I-I′, Eocene conglomerates [*Abbott and Smith*, 1978]; J-J′, Pelona and Orocopia Schists [*Dillon and Ellig*, 1993]. Four-letter codes (e.g., SNGV, SnGr, Baja) label blocks with motion specified in Table 3.

fault slip is often poor, and for simplicity we specify constant relative motion when possible, changing at plate motion reorganizations at 19.0 and 12.5 Ma. Selected finite rotations for the model are presented in Table 3, with the complete set available in the auxiliary material[1].

[18] Our global plate circuit differs somewhat from previous work, most recently updated by *Atwater and Stock* [1998], because of recent documentation of nonrigid behavior of the African and Antarctic plates [*Chu and Gordon*, 1999; *Lemaux et al.*, 2002; *Lemaux*, 2000; *Cande et al.*, 2000]. Similar to Atwater and Stock, we use *Cande et al.*'s [1995] Pacific-Antarctic rotations and *Norton*'s [1995] refinement of *Klitgord and Schouten*'s [1986] North America-Africa rotations. The difference between the revised circuit and that of *Atwater and Stock* [1998] is shown in Figure 5. The difference resulting from using the Antarctic-Nubia (West Africa) rotation of *Lemaux et al.* [2002] for C5o (∼11 Ma) is fairly small, but the C6o (∼20 Ma) rotation of *Lemaux* [2000] shifts the reconstructed position of the Pacific plate south by ∼100 km relative to the Antarctic-Africa (mostly East Africa) rotation of *Royer and Chang* [1991] used by Atwater and Stock. Revisions to the C13o (∼33 Ma) position are slightly larger and much more uncertain. The large uncertainty results primarily from the uncertainty of *Cande et al.*'s [2000] East Antarctica-West Antarctica rotation, but also from the extrapolation we used to estimate the Antarctic-Nubia rotation with minimal direct data. Relative to previous circuit models, this revision increases the predicted strike-slip component of Pacific-North America motion near 20 Ma and decreases the predicted extensional component for ages older than 20 Ma. Our forward model for the global circuit is not a direct sum of the best fit rotations for each plate pair. Instead, we modified the Antarctic-Nubia and the East Antarctica-West Antarctica rotations near the limits of their uncertainties to achieve several goals including minimizing the predicted strike-slip component of Pacific-North America motion (thereby minimizing implied strike-slip motion within North America) and having nearly constant Antarctic-Nubia motion. Our circuit includes a counterclockwise (extensional) change in Pacific-North America motion at about 24 Ma as suggested by *McCulloch* [1989]; this change should be viewed as an interpretation consistent with the global circuit uncertainties rather than as an observation. Net Pacific-North America rotations at selected times are presented in Table 3, with the complete input set in the auxiliary material. Reconstruction figures are based on the

Table 3. Continental Reconstruction Model[a]

Plate/Block 1	Plate/Block 2	Age, Ma	Finite Rotation Latitude, °N	Finite Rotation Longitude, °E	Finite Rotation Angle, deg
Pac	NoAm	12.3	53.96	−70.90	9.21
Pac	NoAm	17.4	55.11	−69.23	12.10
Pac	NoAm	24.1	54.90	−69.74	14.84
Pac	NoAm	28.4	54.15	−72.00	16.91
SNGV	NoAm	12.5	64.00	−65.20	2.89
SNGV	NoAm	19.0	61.30	−79.90	4.84
SNGV	NoAm	28.7	61.40	−83.00	5.26
SnGr	NoAm	12.3	53.93	−70.79	9.22
SnGr	NoAm	19.0	50.10	−93.80	17.93
SnGr	NoAm	28.7	49.10	−98.00	20.57
Carz	SnGr	12.5	39.30	−113.60	−9.59
Carz	SnGr	19.0	39.40	−114.40	−15.66
SBCh	SnGr	12.5	34.27	−120.45	49.00
SBCh	SnGr	19.0	34.32	−120.40	90.00
Baja	NoAm	12.5	59.00	−63.90	6.34
Baja	NoAm	19.0	61.20	−9.50	5.10
Baja	NoAm	28.7	55.0	13.30	4.94
SMOc	NoAm	12.5	−25.30	−56.30	−0.94
SMOc	NoAm	28.7	−27.40	−65.00	−1.00
ColP	NoAm	28.7	40.00	−112.00	1.80

[a]Finite rotation reconstructs plate 1 from its present position to its position relative to plate 2 at the indicated age by counterclockwise-positive angle. See Figure 4 for plate labels, plus NoAm, North American plate; Pac, Pacific plate; SMOc, Sierra Madre Occidental; and ColP, Colorado Plateau (Figure 6). See the auxiliary material for the complete rotation set.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/tc/2003TC001621.

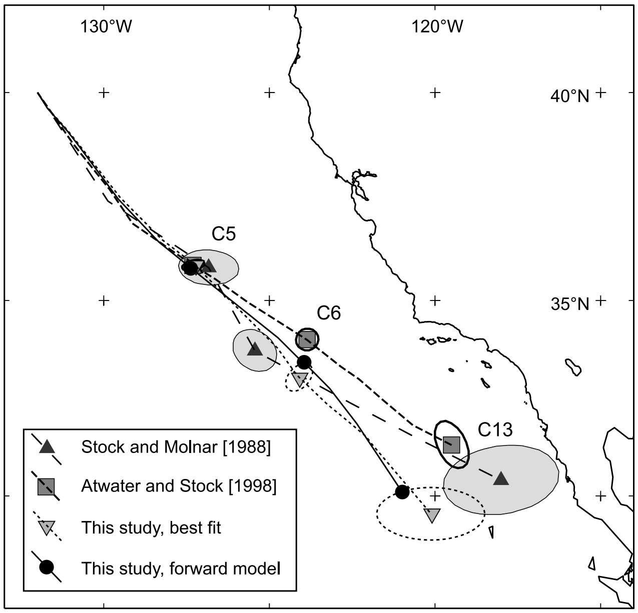

Figure 5. Comparison of Pacific-North America relative motion solutions by global plate circuit, with 95% confidence ellipses. The best fit result for this study uses similar North America-Africa and Pacific-Antarctic finite rotations to those of *Atwater and Stock* [1998] but uses Antarctic-Nubia (west Africa) rotations from *Lemaux et al.* [2002] and *Lemaux* [2000] and for C13 adds motion between East and West Antarctica from *Cande et al.* [2000]. The forward model perturbs several of the more uncertain rotations within their uncertainties as described in the text.

assumption that this circuit model is correct, with evaluation of the assumption reserved for the Discussion section.

[19] For the reconstruction of North America, a fundamental constraint to satisfy is the standard assumption that current Pacific plate oceanic crust has never been subducted beneath North America. As observed by *Stock and Molnar* [1988], among others, most plate circuit calculations require large-magnitude extension in the southern Basin and Range Province to satisfy this constraint. The oldest Pacific crust adjacent to the continental margin is anomaly C10 ($\sim$29 Ma), just south of Pioneer fracture zone. Our circuit restores this older oceanic crust to the current position of northern Baja California in the frame of rigid North America (Figure 6), somewhat west of previous models. To avoid overlap, we include about 220 km of extension since 30 Ma in the Basin and Range Province of northern Mexico, divided between the Sonoran province, bounded by the Gulf of California and the Sierra Madre Occidental, and the Chihuahuan province, east of the Sierra Madre Occidental. Considering geologic evidence that significant extension in the Sonoran province was underway by 25 Ma [*Nourse et al.*, 1994; *Gans*, 1997] and also that given the direction of Pacific-North American motion, extension is necessary for the continental margin to remain in contact with the Pacific plate, we specify westward motion of northern Baja California by rotation about a pivot near its southern end, accompanied by westward motion of the adjacent Alta California blocks.

[20] Using a Sierra Nevada to Colorado Plateau restoration following *Wernicke et al.* [1988], *Wernicke and Snow* [1998], or *Snow and Wernicke* [2000] through the Las Vegas corridor implies that some of the 26–27 Ma and 22–24 Ma volcanic centers will reconstruct slightly north of the slab windows (Figures 3c–3f) that we interpret as their cause. The mismatch is much worse if instead the reconstruction is based on only about 300 km of total motion across the Gulf of California [e.g., *Dickinson*, 1996, 1997; *Oskin et al.*, 2001]. Our reconstruction model has a similar extensional component to the *Wernicke et al.* [1988] and *Snow and Wernicke* [2000] models, but has about 20–40 km more right-lateral strike-slip motion than those models. We do not include the significant clockwise rotation of the Sierra Nevada block interpreted by Snow and Wernicke because it is difficult to reconcile with post-16 Ma extension at 40–43°N and because it seems only weakly supported by the original data. Our model successfully aligns the mid-Tertiary volcanic centers with slab windows for both $\sim$27 Ma and $\sim$23 Ma (Figure 7). The older group that includes the Morro Rock-Islay Hill complex aligns with the initial window between the northern edge of the Monterey plate and the southern edge of the Juan de Fuca plate at the Pioneer fracture zone (Figure 7a), and the northern members of the younger group, including the correlated Pinnacles and Neenach volcanic rocks and several groups in the San Emigdio and Santa Cruz Mountains, align with the window resulting from subduction of the Pioneer-Mendocino spreading segment (Figure 7b). More widely scattered volcanic rocks to the south align with the window between the Monterey plate and the southern edge of the Juan de Fuca plate.

[21] Increased offset of the Sierra Nevada and the California Coast Ranges propagates through the model to other blocks assumed to move with them, including Baja California and the Oregon Coast Range. The northward component of the Oregon Coast Range relative to stable North America since 29 Ma exceeds 100 km in our model. We assume this convergence is accommodated on a combination of thrust faults and northwest striking right-lateral, strike-slip faults, primarily in western Washington.

[22] Describing motion of Baja California requires a choice of reference frame, as we assume that formerly adjacent areas of western Mexico all have moved as well. Capture of the Magdalena fragment of the Cocos plate by the Pacific plate at 12–13 Ma [*Lonsdale*, 1991] places strong constraints on the reconstruction of the Mexican blocks. At 12.5 Ma, the southeast corner of this plate fragment reconstructs to 20°N, 106°W, adjacent to the continental margin in the Jalisco area in rigid North America coordinates. Our strike-slip budget based on matching the volcanic rocks to the slab windows also brings the southern tip of Baja California this far south, so the southern coastline of Mexico must be restored inland to avoid

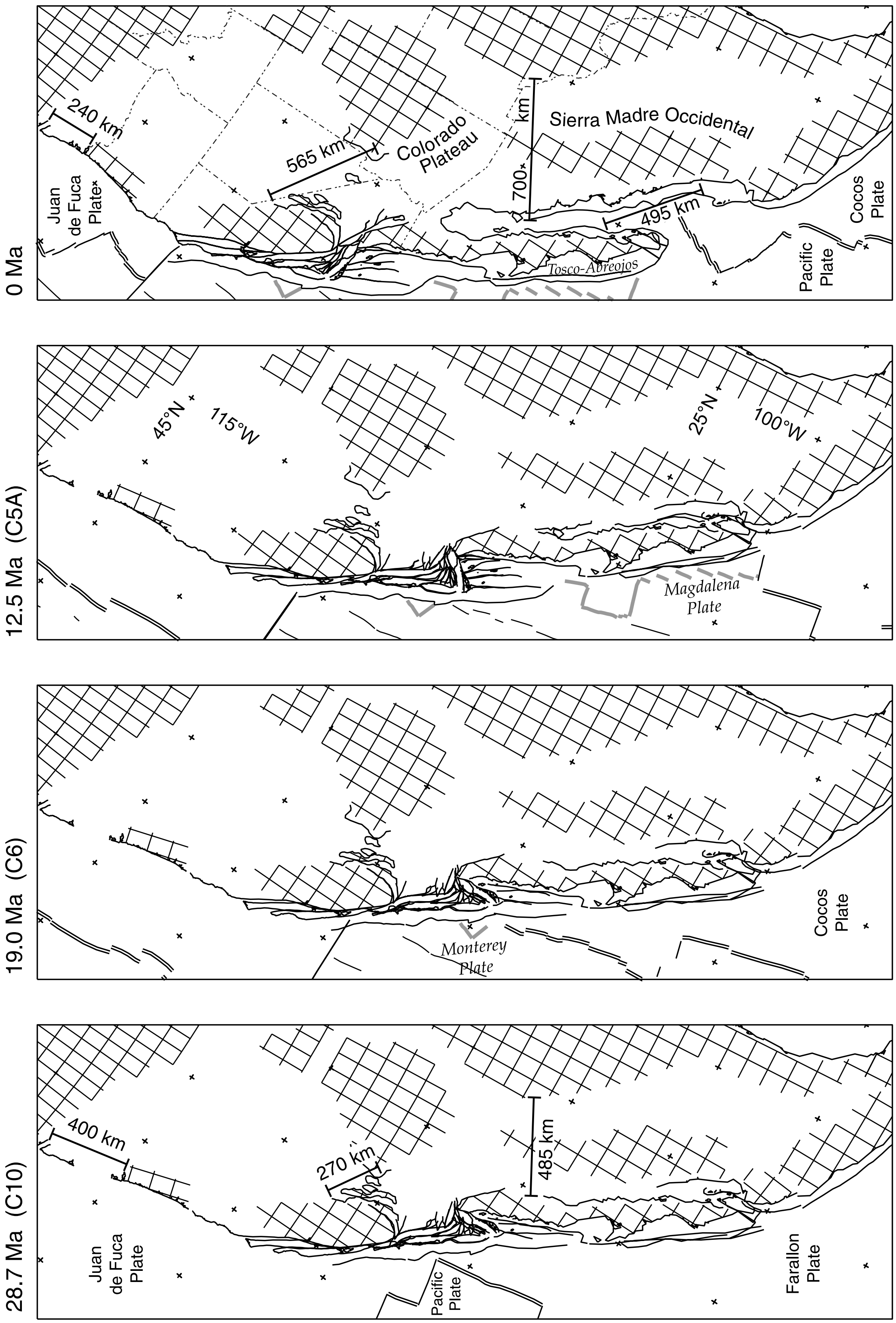
0 Ma
240 km
565 km
Colorado Plateau
700 km
Sierra Madre Occidental
495 km
Juan de Fuca Plate
Cocos Plate
Pacific Plate
Tosco-Abreojos
12.5 Ma (C5A)
45°N
115°W
25°N
100°W
Magdalena Plate
19.0 Ma (C6)
Cocos Plate
Monterey Plate
28.7 Ma (C10)
400 km
270 km
485 km
Juan de Fuca Plate
Pacific Plate
Farallon Plate

Figure 6

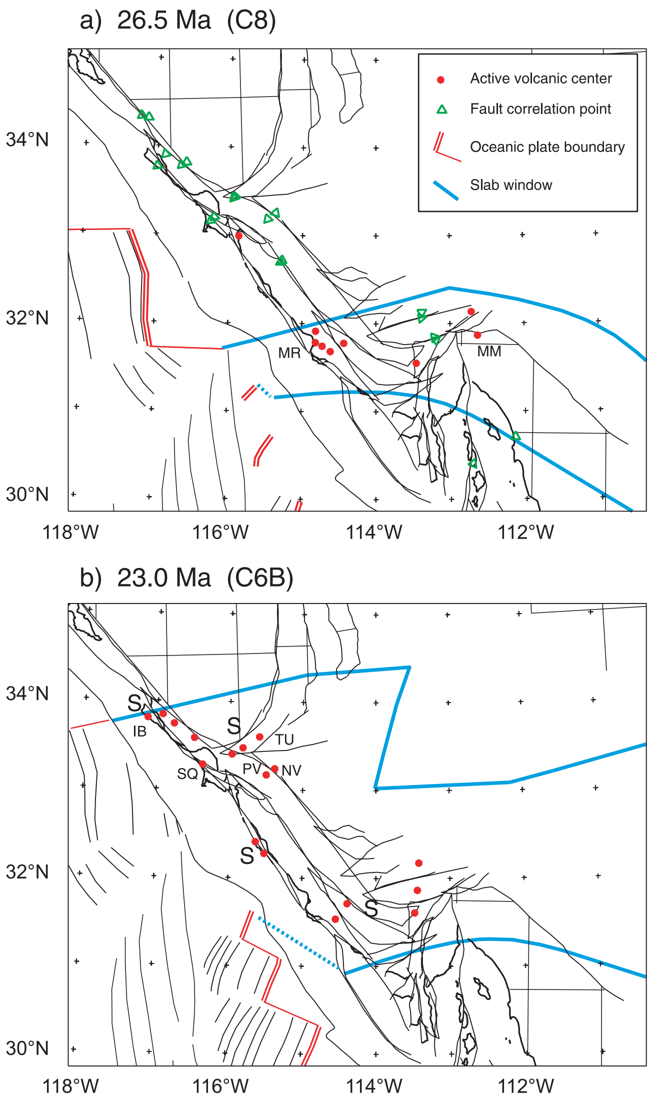

Figure 7. Reconstruction model showing positions of mid-Tertiary volcanic rocks relative to evolving slab windows north of the Monterey plate. (a) The 26.5 Ma (C8) reconstruction shows positions of 27–26 Ma volcanic centers, (b) 23.0 Ma (C6B) reconstruction shows positions of 24–22 Ma volcanic centers. With the exception of the Carmel area volcanic rocks, all volcanic centers can be restored to the slab window at their time of initial eruption. Slab windows are from Figures 3d and 3f but in North America fixed coordinates. "S" indicates a basin analyzed in Figure 9 showing rapid subsidence; triangles are fault correlation points from Figure 4.

overlap. We accommodate this motion on features recognized as having late Miocene extension [*Henry and Arranda-Gomez*, 2000], though probably using larger motions than most workers would expect. Relative to the southern Sierra Madre Occidental, post-12.5 Ma motion of Baja California is modeled as 495 km (Figure 6); relative to rigid North America, post-12.5 Ma motion is 515 km.

[23] As has been noted in previous compilations, our dates of volcanism show little activity from 22 to 19 Ma and widespread renewed activity in southern California from 18 to 14 Ma. In the Santa Maria and Los Angeles basins, these lavas have field relations showing that eruptions were contemporaneous with major extension [*Crowell*, 1987; *Wright*, 1991; *Stanley et al.*, 1996]. In current coordinates, older units are generally northwest of younger units, but reconstructing the eruption positions indicates a west-to-east progression of activity (Figure 8). The setting of these lavas, especially their relation to the capture of the Monterey plate by the Pacific plate, has been the subject of recent debate. *Nicholson et al.* [1994] and *Bohannon and Parsons* [1995] infer that the subducted Monterey plate slab under the California Borderland moved with the Pacific plate after 19 Ma, driving extension in the overlying plate. *Dickinson* [1997] argued that the existence of the volcanic rocks is better explained if instead the slab continued to subduct, separating from the never subducted fragment and thereby opening a slab window. Our interpretation of the capture of the Monterey plate first by the Cocos plate, then by the Pacific plate allows a quantitative test of Dickinson's interpretation. There are few direct constraints on the position of the break between Cocos and Monterey plates, but if a position is chosen, the growth of the slab window will be predicted by the fairly well known relative motion of the Cocos and Pacific plates.

[24] A position for the initial break just west of the oldest volcanic centers in and around the Santa Maria Basin and offshore on San Miguel and Santa Rosa Islands can explain the eastward progression of volcanic activity without violating constraints imposed by observations of dipping reflectors interpreted as top and bottom of subducted Monterey plate crust under the offshore Santa Maria Basin [*Tréhu*, 1991; *Miller et al.*, 1992; *Nicholson et al.*, 1992], and under Monterey Bay and Santa Cruz [*Page and Brocher*, 1993]. The eastward growth of the slab window predicted by Cocos-Pacific motion is adequate for the slab window to grow to extend under the ~16 Ma volcanic rocks of the Peninsular Range-Baja block (GV, SJ, RB) by 16 Ma (Figure 8c). The more southerly locations we advocate based on 27–22 Ma volcanic rocks also allow associating the ~17 Ma volcanic rocks near San Luis Obispo (YM2, OF, LM2) with the north end of the Monterey plate slab window (Figure 8c), but do not place the ~16 Ma volcanic

Figure 6. Reconstruction model showing positions of blocks of western United States and Mexico at important times. Reference frame is fixed to North America; map projection is oblique Mercator about 27°N, 2°W, with projection equator near the center of each panel. Modeled extension in northwest Mexico is indicated by the increase in width from 485 to 700 km. Total motion of Sierra Nevada relative to Colorado Plateau is 295 km since 29 Ma, and motion of Baja California relative to the Sierra Madre Occidental is 495 km since 12.5 Ma.

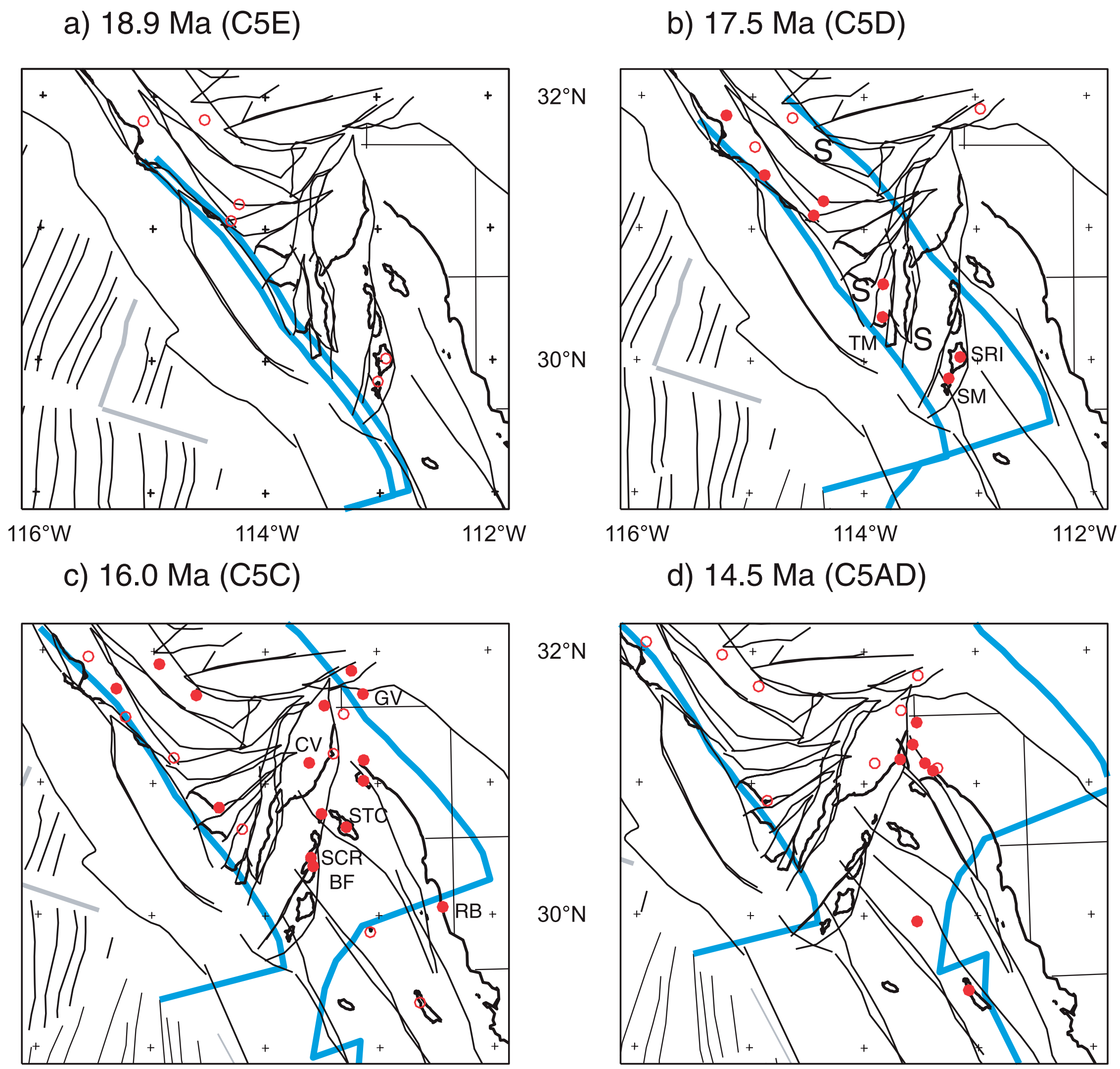

Figure 8. Reconstructions of 19–14 Ma volcanic centers compared with a slab window model east of the captured Monterey plate. Within each frame, volcanic centers with preferred dates at the reconstruction time or less than 1.5 Myr prior to it are plotted as solid circles; other volcanic centers with age uncertainties encompassing the reconstruction time are plotted as open circles. Other symbols are as in Figure 7. The initial position of the break at 19.1 Ma between the captured Monterey plate, and its slab is not known independently, but is assumed to lie west of the older volcanic rocks, near the Hosgri fault. The subsequent evolution of the slab window geometry (bold lines) is assumed to be governed by Cocos-Pacific relative plate motions. Within dating uncertainties, all volcanic centers except JV east of the map edge can be restored to above the slab window at their time of initial eruption. North America fixed coordinates.

rocks at Rosarito Beach and San Clemente Island (RB, SCL) past the southern limit of the possible slab window.

5. Discussion and Implications

5.1. Slab Windows and Basin Subsidence

[25] In many cases, the coastal California lavas are interbedded with marine sedimentary rocks that allow interpretation of the vertical motion of the basin relative to sea level. Water depth at the time of deposition can be inferred from population statistics of benthic foraminifera and other microfossils, and corrections for sediment compaction and isostatic loading allow interpretation of the basin subsidence in the absence of sediment input [e.g., *Dickinson et al.*, 1987]. Most of the basins associated with volcanic rocks that we attribute to slab windows show a brief period (<2 Myr) of rapid subsidence synchronous with volcanism, followed by slow subsidence of variable but often extended duration (often 10–20 Myr). This pattern is

consistent with rapid extension of cold lithosphere over recently introduced hot asthenosphere. Analyses of some of the better documented histories of basin paleobathymetry and corrected thermotectonic subsidence (Figure 9) show two principal times of rapid subsidence at 24–23 Ma and 18–17 Ma, times we interpret that the slab window area grew most rapidly. We speculate that other nearby basins of similar ages show similar subsidence histories, but because the sediments are largely nonmarine, we do not have a good record of vertical motion.

[26] One of the oldest documented subsidence events is in the Año Nuevo basin (Figure 9a), west of the San Gregorio fault in central California. Some Neogene strata from this basin crop out onshore, but the basin is best documented in the offshore subsurface. A petroleum well 20 km offshore from Pigeon Point (Shell OCS P-036-1; 100-m water depth) encountered Upper Cretaceous marine sedimentary rocks overlain by a 115-m section of Oligocene marine clastic strata interbedded with volcanic rocks [*Dunkel*, 1997]. Overlying lower Miocene strata contain benthic foraminiferal assemblages diagnostic of abyssal depths (>4000 m (F. W. Bergen, unpublished data, 1976)). The exact timing of initial subsidence is estimated at about 23 Ma from correlation of dated volcanic rocks onshore at Pescadero Beach [*Taylor*, 1990] with volcanic rocks in equivalent stratigraphic position in the well. A long period of tectonic quiescence was terminated by rapid uplift at about 15 Ma.

[27] Subsidence of similar age is well documented in the Point Arena basin (Figure 9b), west of the San Andreas fault in northern California. *Loomis and Ingle* [1994] have compiled age and depth data from limited onshore outcrops and three wells 14–20 km offshore. Middle Eocene sedimentary rocks are overlain by the ~23 Ma Iversen Basalt [*Turner*, 1970] (unit IB in Table 1 and Figure 1), in turn overlain by lower Miocene sedimentary rocks showing rapid deepening to lower bathyal depths (2000–4000 m). Offshore, sedimentation at lower bathyal depths continued until rapid uplift in the Pliocene.

[28] In the Tejon embayment, southernmost San Joaquin basin, *Goodman and Malin* [1992] have documented a complex tectonic history at an inland site east of the reconstructed positions of the La Honda and Point Arena basins (Figure 7b). The thicker sedimentary sections of the area have been penetrated by numerous petroleum wells, and show mostly nonmarine and shallow marine conditions for much of middle Eocene through early Oligocene time, deepening to lower middle bathyal to lower bathyal depths during late Oligocene time [*Nilsen*, 1987; *Lagoe*, 1987a; *Goodman and Malin*, 1992]. Local relations indicate that the ~23 Ma Tunis volcanic unit (TU) which is interstratified with lower Miocene marine and nonmarine sedimentary rocks, was deposited during active normal faulting. Lower Miocene sedimentary rocks show continued basin subsidence, followed by intervals of uplift in the middle Miocene, with the basin filling to a nonmarine environment near the end of the late Miocene.

[29] The Cuyama basin, which reconstructs about 275 km south-southeast of the Tejon site (Figure 7b), also shows rapid subsidence at about 23 Ma. At the western margin of the basin, the Simmler Formation contains nonmarine sedimentary rocks interbedded with basalt (SI) radiometrically dated about 23 Ma [*Ballance et al.*, 1983]. Most of the subsidence history has been inferred from a petroleum well in Cuyama Valley, on the west central side of the basin [*Lagoe*, 1987a, 1987b]. Here, a thin, uppermost Oligocene sandstone unit containing neritic fauna (0–150 m water depth) overlies middle Eocene marine strata with significant angular unconformity. Strata containing lower middle bathyal fauna (1500–2000 m) immediately overly the thin neritic facies, indicating rapid subsidence at about the time of eruption of the Simmler Formation basalts. A shoaling back to neritic conditions began about 22 Ma, following the short period of deep marine conditions (Figure 9d). The thickness of sediment fill is insufficient to account for the magnitude of shoaling, implying tectonic uplift. At about 19 Ma, another episode of abrupt subsidence began and water depths rapidly reached middle bathyal depths (1000–2000 m). Subsidence continued until a second abrupt uplift event at about 16 Ma.

[30] The Santa Maria basin is characterized by Miocene marine strata generally overlying Mesozoic units. Initial subsidence of the basin was approximately coeval with increased volcanic activity in central and southern California at about 18–17 Ma. A composite section near Point Sal [*McCrory et al.*, 1995] shows the familiar pattern of rapid initial subsidence associated with volcanism. Tuffs in the lowermost Neogene nonmarine strata are correlative with the Tranquillon Volcanics (TM) and have been radiometrically dated at 17.4–17.7 Ma [*Stanley et al.*, 1996]. The transition from neritic to bathyal marine strata is abrupt [*Stanley et al.*, 1996]. Bathyal depths, initially reached about 17 Ma, are found through most of the strata of middle and late Miocene age, indicating that sediment input roughly balanced slow subsidence.

[31] The Santa Barbara-Ventura basin differs from the nearby Santa Maria basin in having significant thicknesses of Upper Cretaceous and lower Tertiary strata preserved. Our backstrip plot for this basin (Figure 9f) is based on a well (Exxon OCS-P 188-2) from the offshore Hondo field. The deepest rocks penetrated in the well are nonmarine strata of middle Eocene through early Miocene age. Lower Miocene, shallow marine strata apparently conformably overlie these strata. Deep marine strata with interstratified volcanic tuffs immediately overlie the shallow marine deposits, indicating volcanism synchronous with rapid subsidence. Timing of subsidence is similar to the nearby Point Sal site, with rapid subsidence starting at 19–18 Ma and ending at 17–16 Ma. Onshore surface sections record bathymetric deepening at about 22–24 Ma [*Ingle*, 1980; *Stanley et al.*, 1994] in the Santa Barbara-Ventura basin, but the actual timing of initial abrupt subsidence has not been determined at these sites.

[32] Generally similar histories can be found for several basins not analyzed in Figure 9. In the La Honda basin, rapid subsidence associated with volcanism and faulting occurred about 20–25 Ma [*Stanley*, 1985, 1988, 1990; *Dickinson et al.*, 1987]. These events, previously attributed

to transtension and pull-apart tectonics along the San Andreas fault system, are here interpreted as resulting from rapid slab window development following subduction of the spreading ridge segment between the Mendocino and Pioneer fracture zones. A similar interpretation may also explain rapid subsidence, normal faulting, and volcanism that occurred about 20–25 Ma in some small, nonmarine sedimentary basins along the San Andreas fault in southern

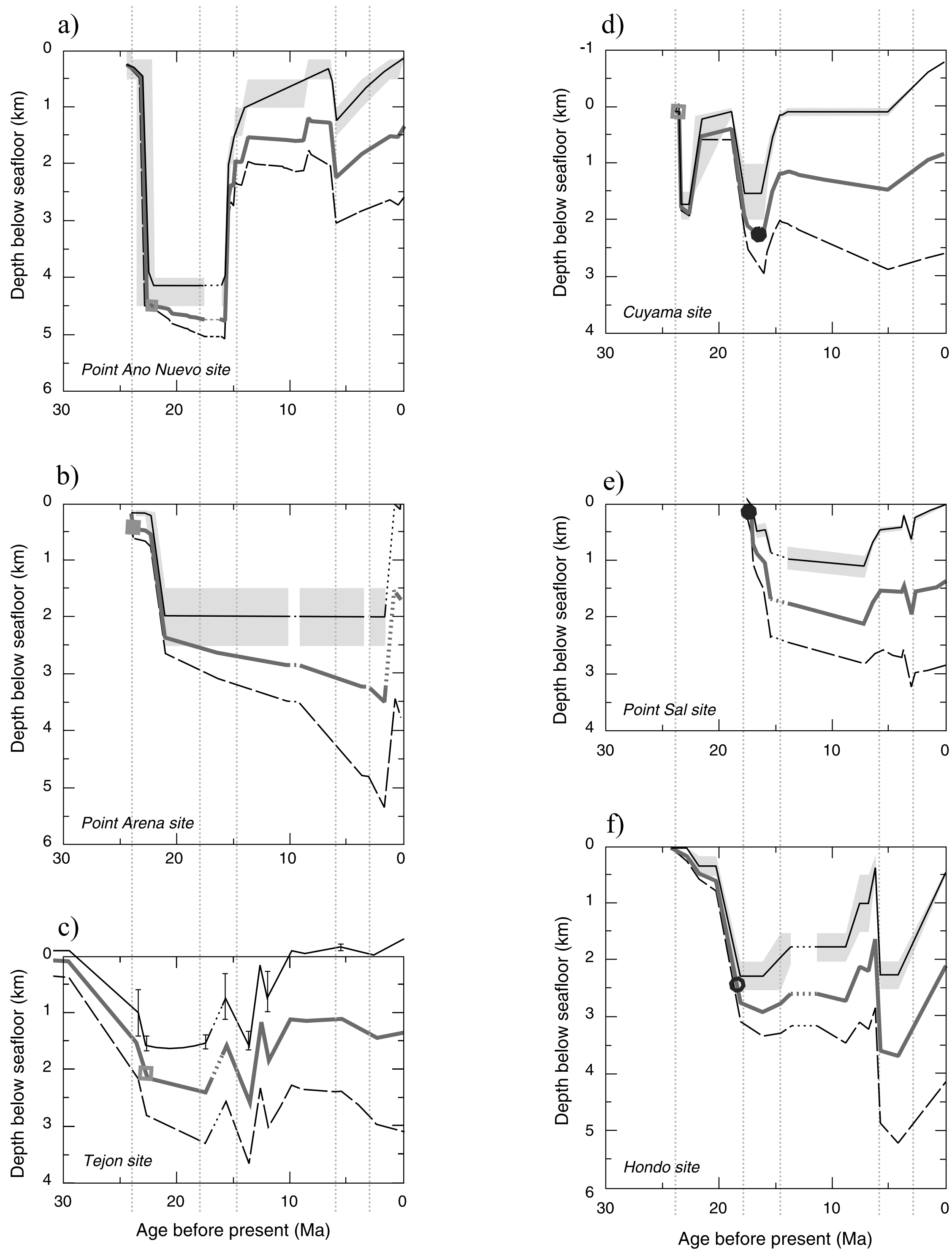

Figure 9

California, including the Plush Ranch [*Cole and Stanley*, 1995], Soledad [*Hendrix and Ingersoll*, 1987], and Diligencia basins [*Spittler and Arthur*, 1982; *Davisson et al.*, 1992].

[33] In the Los Angeles basin, rapid subsidence is thought to have begun about 18 Ma [*Mayer*, 1991] and was followed shortly thereafter by extensive volcanism [*Wright*, 1991]. These events, previously attributed to pull-apart tectonism associated with strike slip faulting [*Crowell*, 1974, 1987] or to the creation of a sphenochasm during transrotation of the western Transverse Ranges [*Luyendyk and Hornafius*, 1987, p. 279], are here interpreted as resulting from rapid slab window development following breakup of the Monterey plate into eastern and western fragments, continued subduction of the eastern fragment, and capture of the never subducted western fragment by the Pacific plate.

[34] The widespread occurrence of rapidly subsiding basins at about 23 Ma has certainly been previously described, notably by *Stanley* [1985, 1988, 1990], *McCulloch* [1989], and *Tennyson* [1989]. Stanley suggested that the synchroneity was the result of regional transtension, but did not specify the cause of the transtension. McCulloch suggested the synchroneity was a result of a change in Pacific plate motion, though subsequent studies [e.g., *Atwater and Stock*, 1998] have not found evidence for this change. Tennyson, while not suggesting a specific mechanism for the synchroneity, advocated an arc setting for the basins based on an interpretation that they reconstruct north of the Mendocino transform according to the plate circuit of *Stock and Molnar* [1988]. She also noted similarities between these California basins and coeval basins in southwest Arizona. The interpretation of an arc setting instead of a transform setting becomes unnecessary with the increase in inferred inland strike-slip faulting discussed above, and with the revision of the plate circuit shown in Figure 5, leading to the reconstruction of Figure 7b.

[35] Similarities between the California and Arizona basins suggest a mechanism that temporarily brought Basin and Range Province extension to near the continental margin at 23 Ma. The common occurrence of volcanism nearly synchronous with initial extension in the Basin and Range Province has been documented by *Gans et al.* [1989]. They advocate that weakening by magmatic intrusion can trigger extensional deformation in crust already under tension. For much of the Basin and Range Province, synextensional volcanism occurred in an arc setting, but the weakening effects in a slab window setting should be at least as strong. For relatively thin crust near the continental margin, the transition from subduction zone to slab window setting can probably also cause significant weakening by conductive heating of the base of the crust. What we see as the dominant factor in driving extension and subsidence at about 23 Ma is the rapid growth of slab window area as the slab window between Mendocino and Pioneer fracture zones merged with the older slab window south of Pioneer (Figure 7). Greater length of the Pacific-North America plate boundary would increase the driving force for Basin and Range Province extension [*Bohannon and Parsons*, 1995] while thermal effects above the slab-free mantle would simultaneously weaken the crust. The records of individual basins (Figure 9) indicate that subsidence driven by nearby faulting can overwhelm any uplift caused by heat input, but after faulting ceases slow subsidence is consistent with conductive cooling.

5.2. Comparsion With Other Reconstructions

5.2.1. Sierra Nevada

[36] Compared with most reconstructions, we place the Sierra Nevada and Baja California farther south relative to stable North America. The discrepancy between our model and the Sierra Nevada-Colorado Plateau reconstruction in the Las Vegas corridor of *Wernicke et al.* [1988], *Wernicke and Snow* [1998], or *Snow and Wernicke* [2000] is not serious, and is resolvable by adding less than 50 km of strike slip to their model. *Wernicke et al.* [1988] determined 247 ± 56 km of motion, and the detailed model of *Snow and Wernicke* [2000] includes 277 km of motion at the north edge of their corridor (~37°N). Our reconstruction the Sierra Nevada block relative to North America has 319 km of motion at this location, about 295 km relative to our reconstruction of the Colorado Plateau (Figure 6). For readers interested in pursuing specific reconstruction constraints outlined by *Wernicke et al.* [1988], the stated uncertainties of their D2–D4 segment in the center of the corridor allow a 30-km increase in strike slip, and the constraints across Owens Valley on the west and Las Vegas Valley on the east (their E1–E2, A1–A2, and C1–C2 segments) are not firm enough to exclude an additional 20 km of strike slip. As our model assumes both a plate circuit (Figure 5) and timescale [*Cande and Kent*, 1995], it is worth inspecting whether other adjustments might be equally plausible.

[37] The key relations guiding our interpretation of increased strike-slip motion are placing the Iversen Basalt (IB) south of the Mendocino fracture zone at 23.0 Ma (chron C6B), and the Morro Rock-Islay Hill complex

Figure 9. Backstrip plots for selected sites along the California continental margin showing vertical motion of the basin floor through time. Top curve is mean paleobathymetry estimated from microfossils. Bathymetric range of various foraminiferal assemblages is denoted by the shaded area around this curve. Middle curve is an estimate of mean subsidence and uplift of basin strata owing to tectonic driving forces, including crustal thinning, thermal decay, and flexural behavior. Bottom curve is an estimate of total basin subsidence, before correction for isostacy and sediment compaction. Circles and squares represent first occurrence of volcanic rocks within basin strata. See Figure 2 for the present location of the sites. See Figures 7b and 8b for the reconstructed positions of the sites at the time of initial subsidence. See the auxiliary material for sources of data. For discussion of technique, see *Steckler and Watts* [1978], *van Hinte* [1978], and *Dickinson et al.* [1987].

south of the Pioneer fracture zone at 26.5 Ma (chron C8, Figure 7). Alternatives to increasing the strike slip within North America include revising the plate circuit to predict less Pacific-North America motion and revising either the reversal timescale or the volcanic ages such that the volcanic centers would correspond to later magnetic anomalies. Our revised plate circuit (Figure 5) has been chosen to minimize the strike-slip component of Pacific-North America motion within the formal uncertainties of the reconstruction. The large changes between successive plate circuit models, however, hardly inspire confidence that the formal uncertainties describe the true uncertainties of the circuit. We note that changing the position of the Pacific plate to the northwest does not correspond to the maximum uncertainty direction of any of the components of the plate circuit, but could result from revising Africa-North America motion in a fashion that shifts the Pacific plate north while also revising Pacific-Antarctic motion shifting the Pacific plate west. Such an adjustment of the plate circuit appears to deserve further consideration.

[38] The alternative of revising the age relations is not especially appealing. The geometric constraints could be satisfied by assuming that the volcanic ages are systematically too old, or that the anomaly ages are too young, such that for example the >23 Ma Iversen Basalt might have formed during chron C6A. The required shift in the CK95 timescale is in the opposite direction from two very credible alternative calibration points. *McIntosh et al.* [1992] correlate C10n/C10r with a well dated reversal at 28.0 Ma instead of 28.74 Ma, and *Shackleton et al.* [2000] dated the Miocene/Oligocene boundary in C6B at 22.9 Ma instead of 23.8 Ma. Accepting these timescale revisions would require further revisions in the strike-slip budget or the plate circuit by an additional 30–40 km. Possible bias in the sample ages would involve similar errors in multiple dates from different units. For the case of the K-Ar dates for the Iversen Basalt reported by *Turner* [1968], replicating the dates is probably a worthwhile exercise.

5.2.2. Hayward and Calaveras Faults

[39] *McLaughlin et al.* [1996] and *Wakabayashi* [1999] have recently suggested greater displacements than most previous authors for the strike-slip faults east of San Francisco Bay. *McLaughlin et al.* [1996] infer 170 km of offset across the combined Hayward-Calaveras system (correlation points F-F′, Figure 2), and Wakabayashi interprets even more offset. Interpretation of slip on these faults is relatively independent of slip on other faults, so they are not central to our analysis. We find that the position of 16–12 Ma volcanic centers near San Francisco Bay supports the interpretation of large displacements. Figure 10 shows our prediction of the northward motion of the Mendocino transform fault relative to the San Francisco Bay block for 15.5 to 12.5 Ma. Reconstructing an offset of only about 100 km would place the volcanic centers above the Juan de Fuca plate instead of the slab-free mantle at the time of their eruption.

5.2.3. Salinian Faults

[40] Interpretation of slip on faults west of the San Andreas fault has not had the level of agreement between different workers as has slip on the San Andreas fault itself. For the San Gregorio fault, many recent authors have supported *Clark et al.*'s [1984] estimate of 150 km of post-early Miocene offset, correlating features from Pt. Arena to Pt. Reyes on the west with features from Half Moon Bay to Carmel on the east [*Wentworth et al.*, 1998; *Jachens et al.*, 1998; *Burnham*, 1998; *Wakabayashi*, 1999; *Stakes et al.*, 1998]. Nothing approaching a consensus has emerged as to how this offset is distributed farther south. For example, the common interpretation that most of this offset continues on the Sur-San Simeon-Hosgri system has been disputed by *Underwood et al.* [1995] and *Underwood and Laughland* [2001]. They mapped degree of metamorphism of sedimentary rocks of the Franciscan Complex adjacent to these faults, and their analysis can be paraphrased to exclude right-lateral offset of 0–5, 15–100, or 120–140 km because disparate paleotemperatures would be juxtaposed. For simplicity, they prefer an interpretation of 5–15 km offset, at least for the onshore strands of the Sur and San Simeon faults. Our reconstruction, with 145 km offset across these faults, does not conflict with any of their observations. In fact, their strongest thermal anomaly at Cape San Martin reconstructs adjacent to the volcanic rocks near Pt. Año Nuevo (AN) at their eruption time of ~23 Ma (Figure 7b). Our interpretation of large offset on the Sur and San Simeon faults does not conflict with the observation that offset on the Hosgri fault dies out southward [e.g., *Sedlock and Hamilton*, 1991]. Because we interpret very large strains in the onshore Santa Maria basin, the western limit of the Transverse Ranges near Pt Arguello can be close to the southern termination of the Hosgri fault at all times in our reconstruction (Figure 11).

5.2.4. Baja California

[41] The discrepancy between our model and common interpretations of 300–350 km of displacement between Baja California and North America is more serious than other differences, but we are not aware that our model violates any strong constraints. Because we generally follow previous workers in restoring western California slivers relative to these major blocks and in restoring Pacific to North America, our upward revision of slip on faults east of Baja California requires downward revision of strike slip on offshore faults. Our reconstruction of total slip (since 12.5 Ma) on faults west of Baja California, including the Tosco-Abreojos fault along the western continental shelf, is only 170 km. This revision still slightly exceeds the estimate of *Fletcher* [2003] of a maximum of 150 km of strike slip for the western margin faults inferred from local relationships.

[42] Most workers have interpreted the Tosco-Abreojos fault as the principal plate boundary between the North American and Pacific plates at the latitude of northern Mexico for the time interval 12–6 Ma [*Spencer and Normark*, 1979; *Stock and Hodges*, 1989]. To the north, the San Andreas and San Gabriel faults are widely recognized as becoming the principal plate boundary faults during this interval. There has not been a consensus on how to connect the offshore slip in the south with the inland slip to the north under these interpretations. *Ingersoll and Rumelhart* [1999] propose a strike-slip boundary on the

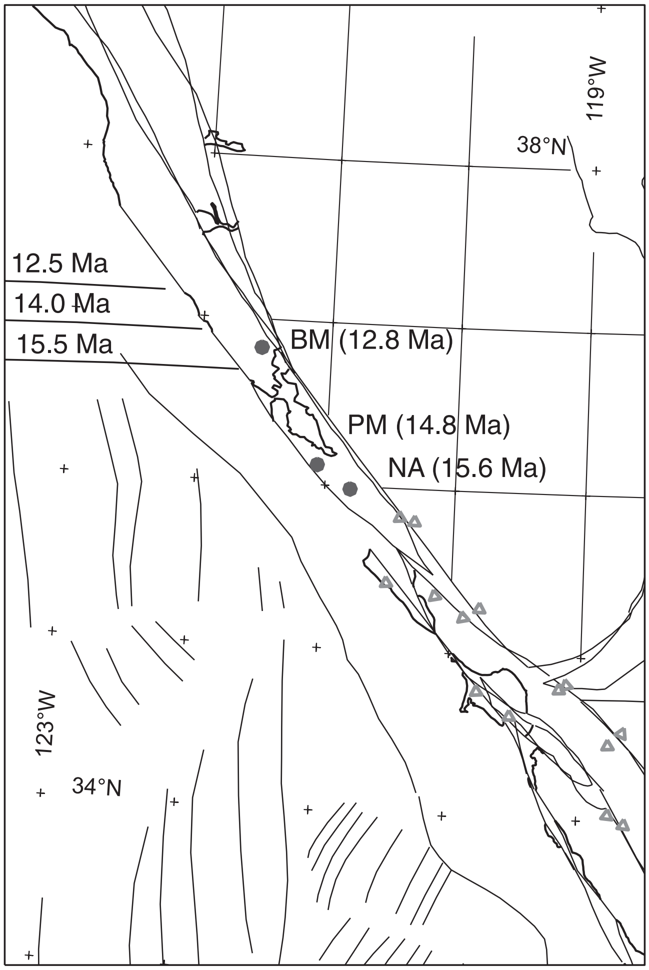

Figure 10. Reconstruction at 15.5 Ma with SNGV block fixed. The position of the active Mendocino transform fault (fixed to the Pacific plate) is shown for this time and younger times 14.0 and 12.5 Ma in this reference frame, approximately showing the progression of the northern limit of the slab window. Solid circles are volcanic centers from Figure 1; triangles are fault correlation points from Figure 4. Following *McLaughlin et al.* [1996], the reconstruction includes 170 km of offset on the Hayward-Calaveras fault system east of the northern San Andreas fault. Offset of SNGV block relative to North America is 270 km at 15.5 Ma and 216 km at 12.5 Ma, evaluated for 37°N, 121°W. Significantly smaller offset on either system would place the New Almaden, Page Mill, and Burdell Mountain volcanic centers over the Juan de Fuca plate instead of over the slab-free mantle at their time of eruption.

west side of the Peninsular Ranges, in contrast with *Crouch and Suppe* [1993] and *Bohannon and Geist* [1998], who interpret no strike slip there. Our interpretation of a more minor role for the Tosco-Abreojos fault eliminates the need to connect slip on these systems. Instead, we interpret that the slip on the San Andreas and San Gabriel faults connected in a simple fashion to faults of the proto-Gulf of California on the east side of the Peninsular Ranges (Figure 11). Slower slip on the San Gregorio and adjacent faults was connected to slip on Borderland faults and the Tosco-Abreojos system via western Transverse range rotation.

[43] *Oskin et al.* [2001] and *Oskin and Stock* [2003] have recently documented about 250 km of opening across a spreading segment of the northern Gulf of California since 6 Ma, with only slightly more opening on the same segment possible since 12 Ma. Prior to 6 Ma, the principal plate boundary must have been either to the west, probably on the Tosco-Abreojos fault, or to the east in mainland Mexico, as suggested by *Gans* [1997]. The region where inactive, pre-6 Ma strike-slip faults would be found among onshore outcrops need not be extensive, perhaps at 28°–31°N in northern Mexico. Elsewhere, including most of the San Andreas fault system except for the San Gabriel fault, the faults active before 6 Ma could have been essentially the same as those after 6 Ma, with a northern San Andreas fault extending southward from the Mendocino triple junction, connecting via a big bend to a largely transform system separating Baja California from mainland Mexico. The internal consistency of our kinematic reconstruction can be evaluated by viewing the animations available in the auxiliary material.

[44] Accepting both our across-fault ties from Figure 2 and our correlation of volcanic units with Pacific plate fracture zones (Figures 7, 8, and 10) requires a restoration of at least 500 km of relative motion between Baja California and North America over the entire time range from 27 to 13 Ma. For 19 to 12.5 Ma, we think a similar conclusion can be drawn by substituting the Sierra Nevada reconstruction of *Snow and Wernicke* [2000] for the volcanic constraint. Adjusting the position of Baja California by 200 km in Figures 6 and 11 for these times requires complete reinterpretation of the strike-slip history of several faults. In particular, the Eocene conglomerate correlation of *Abbott and Smith* [1978] (I-I′ in Figure 4) is difficult to satisfy within 100 km. Also, if the western Transverse Ranges are rapidly moving northward relative to the Peninsular Range prior to 6 Ma, there is little available space for their large rotation until the strike-slip motion is largely complete, but paleomagnetic evidence summarized by *Luyendyk* [1991] indicates that most of the rotation predates 6 Ma.

[45] With Pacific-North America relative motion rates averaging about 50 mm/yr, our interpretation of over 500 km of slip between Baja and North America requires that strike-slip motion started at a minimum age of about 10 Ma. The timing of the model illustrated in Figures 6 and 11 is based on the assumption that the accelerated motion of Baja was a response to the capture of the Magdalena plate fragment by the Pacific plate at about 12.5 Ma. The mechanism for this acceleration would be the same advocated for the onset of rapid extension in the Inner Borderland and Santa Maria basin by *Nicholson et al.* [1994] and *Bohannon and Parsons* [1995] in response to capture of the Monterey plate. Given the motion of the Pacific plate obliquely away from the North American margin, a captured microplate fragment would either

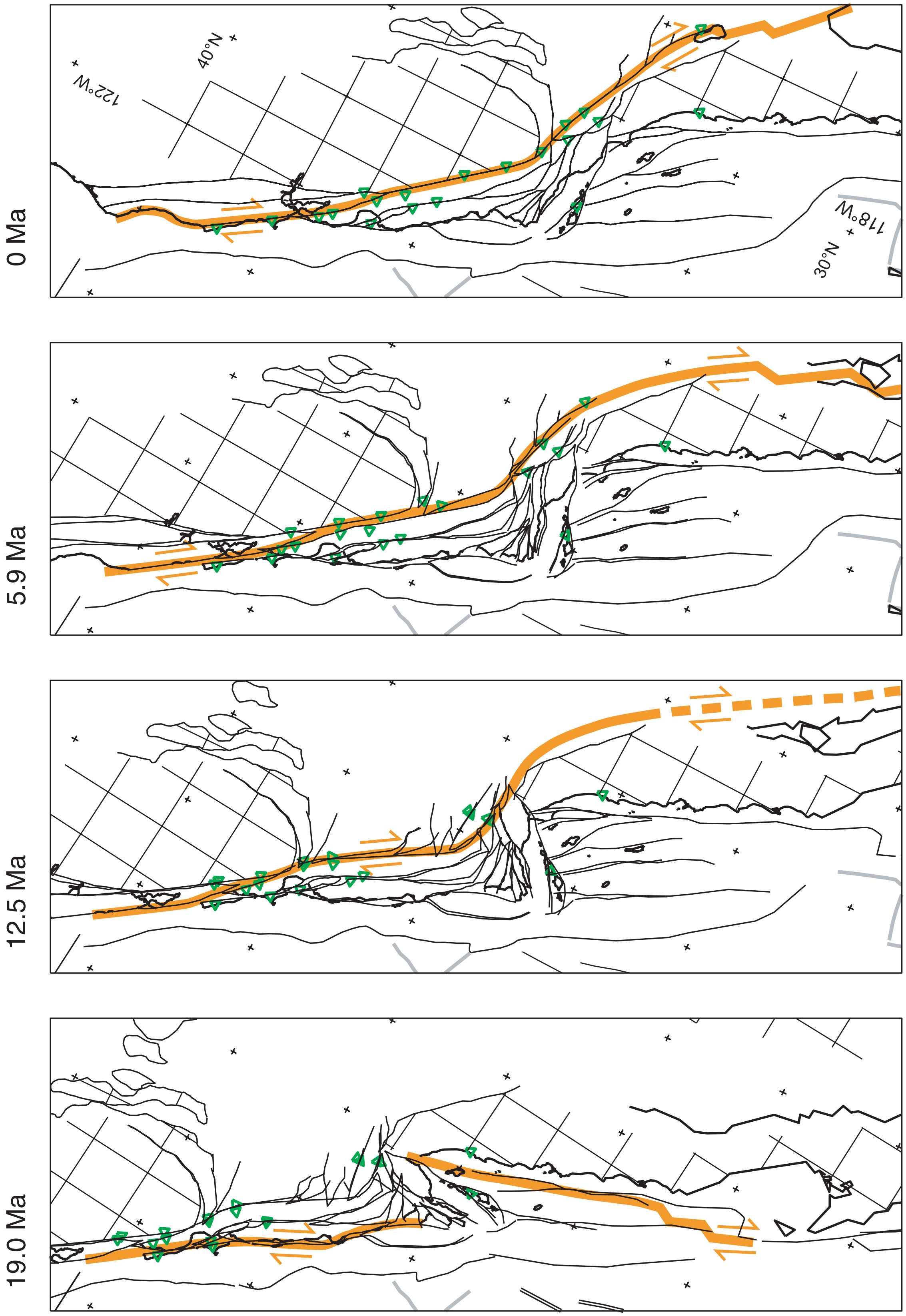

Figure 11

"unsubduct" or extend the continental margin. Apparently, the relevant force balances favor increased extensional deformation of the margin, suggesting that the frictional forces needed to be overcome to reverse the dip-slip component of motion on the subduction zone exceed the strength of the already extending continental crust. The edge of the overriding plate switches to motion much closer to that of the Pacific plate from motion much closer to that of stable North America. *Bohannon and Parsons* [1995] argued that strength considerations require a lag of at least 4 Myr between the cessation of offshore spreading and when the former spreading center becomes stronger than continental crust. The narrower age gap between the cessation of Monterey plate spreading during or after chron C6n (~19.0 Ma) and volcanic units interbedded with sediments recording the early subsidence of the Santa Maria Basin, recently dated at about 18–17 Ma [*Stanley et al.*, 1996], implies that this argument is at best incomplete. *Dickinson* [1997] has suggested that the forces transmitted across oceanic transform faults may resolve this strength problem.

5.3. Subducted Monterey Plate

[46] *Brocher et al.* [1999], who compiled seismic structure results for coastal California, emphasized the apparent continuity of mafic lower crust beneath all of the Coast Ranges from 34°N to 40°N. They interpret this mafic crust as young oceanic crust underthrust during the Neogene, and therefore they question whether slab windows played a role in generating coastal volcanism. While we do not address the exact mode of formation of the northward migrating volcanic group (the primary target of Brocher et al.'s discussion), we disagree that continuity of mafic lower crust constitutes good evidence for lack of a past slab window.

[47] *Brocher et al.* [1999] acknowledge the difficulty of distinguishing whether mafic lower crust was emplaced tectonically or underplated magmatically. We further point out that velocity structure contains no information regarding the time of emplacement of the lower crust. We agree that the best evidence for an underthrust origin of mafic lower crust is continuity with oceanic crust of similar thickness outboard of the continental margin. We argue, however, that any offset or change in thickness of the mafic lower crust can reasonably be suspected as a boundary between blocks of different origin.

[48] As described above, our interpretation of the age pattern of mid-Miocene volcanism in southern California is that the subducting slab broke about 100 km inboard of the continental margin and volcanism migrated eastward with the edge of the former Monterey plate slab as it subducted as part of the Cocos plate (Figure 8). The clearest examples of mafic crust of uniform 5–7 km thickness connecting with normal, nonsubducted oceanic crust are offshore from the Santa Maria basin [*Tréhu*, 1991; *Miller et al.*, 1992] and southwest of Santa Cruz [*Page and Brocher*, 1993]. Only in one transect near Santa Cruz, however, does the uniform thickness continue inland across coastline. Our interpretation that the Monterey plate slab should end near the present coastline can be reconciled with the seismic evidence only if there is a contact with mafic crust of some other origin near the coastline. We think such a contact is a physically reasonable interpretation if the western edge of previously underthrust oceanic crust controlled the location of the break of the Monterey plate slab. Our reconstruction includes about 100 km of post-19 Ma horizontal motion between the terranes west of the San Gregorio-Hosgri fault and the Pacific plate, including the captured Monterey plate fragment. We think that this motion is most simply interpreted as having occurred as strike slip motion on the former subduction zone. This interpretation is fully compatible with that of *Miller et al.* [1992], who argued that local thickening of oceanic crust under the offshore Santa Maria basin was created by motion on a low-angle fault at the top of oceanic crust. We speculate that this thrusting was caused by slight misalignment of the edges of the Monterey slab and older (Jurassic?) oceanic crust, and that the thrusting may have been responsible for a hiatus in sedimentation commonly observed at about 14–12 Ma in the Santa Maria Basin [e.g., *McCrory et al.*, 1995].

6. Conclusions

[49] Our goal in this project was to test the viability of correlating volcanic units with specific slab windows, and to use those correlations to refine tectonic reconstructions. Though some of the resulting reconstructed positions differ from what has commonly been published, we find no serious problems with these positions. Within moderate uncertainties, there is no need to modify either the global plate circuit or the reversal timescale to satisfy the constraints derived from the slab window correlations. Of course, this consistency does not necessarily imply that either our reconstruction, the plate circuit or the timescale is correct, and better testing of the reconstruction will be possible as independent information refines the timescale and plate circuit.

[50] We see our interpretation of a moderate increase in motion of the Sierra Nevada relative to the Colorado plateau or North America as a refinement of previous work, not requiring serious reinterpretations, and not clearly preferable to potential revisions in the plate circuit. Previous estimates of the original position of Baja California have been bimodal, with a majority advocating about 300 km of motion and a minority advocating about 500 km. Our reconstruction of the past positions of coastal volcanic units from 27 to 12 Ma strongly supports the minority view of at

Figure 11. Reconstruction in Pacific fixed coordinates. Bold line highlights the fastest slipping fault in continental crust active or becoming active at the reconstruction time. Major reorganizations are interpreted to be simultaneous with capture of the Monterey plate at 19 Ma and of the Magdalena plate at 12.5 Ma. In this model, the big bend in the San Andreas fault system formed during the 12.5 Ma reorganization and has been straightening since then.

least 500 km of displacement. A direct consequence of this interpretation is that the approximate geometry of the current Pacific-North American plate boundary in California and western Mexico developed at about 10–12 Ma.

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References

Abbott, P. L., and T. E. Smith (1978), Trace-element comparison of clasts in Eocene conglomerates, southwestern California and northwestern Mexico, *J. Geol.*, *86*, 753–762.

Atwater, T. M. (1970), Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, *81*, 3513–3536.

Atwater, T. M., and P. Molnar (1973), Relative motions of the Pacific and North American plates deduced from seafloor spreading in the Atlantic, Indian, and South Pacific Oceans, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, edited by R. L. Kovach and A. Nur, *Stanford Univ. Publ. Geol. Sci.*, *13*, 136–148.

Atwater, T., and J. Severinghaus (1989), Tectonic map of the northeast Pacific Ocean, in *The Geology of North America*, vol. N, *The Eastern Pacific Ocean and Hawaii*, edited by E. L. Winterer, D. M. Hussong, and R. W. Decker, pp. 15–20, Geol. Soc. of Am., Boulder, Colo.

Atwater, T. M., and J. M. Stock (1998), Pacific-North America plate tectonics of the Neogene southwestern United States—An update, *Int. Geol. Rev.*, *40*, 375–402.

Ballance, P. F., D. G. Howell, and K. Ort (1983), Late Cenozoic wrench tectonics along the Nacimiento, South Cuyama, and La Panza faults, California, indicated by depositional history of the Simmler Formation, in *Tectonics and Sedimentation along Faults of the San Andreas System*, edited by D. W. Andersen and M. J. Rymer, pp. 1–9, Pac. Sect., Soc. for Sediment. Geol., Walnut, Calif.

Bartow, J. A. (1991), Geologic map of the northwestern Caliente Range, San Luis Obispo County, California, *U.S. Geol. Surv. Misc. Invest. Map, I–2077*.

Berry, A. L., G. B. Dalrymple, M. A. Lanphere, and J. C. Von Essen (1976), Summary of miscellaneous potassium-argon age measurements, U.S. Geological Survey, Menlo Park, California, for the years 1972–74, *U.S. Geol. Surv. Circ.*, *727*, 13 pp.

Blake, G. H. (1991), Review of the Neogene biostratigraphy and stratigraphy of the Los Angeles basin and implications for basin evolution, in *Active Margin Basins*, edited by K. T. Biddle, *AAPG Mem.*, *52*, 135–184.

Bohannon, R. G., and E. L. Geist (1998), Upper crustal structure and Neogene tectonic development of the California continental borderland, *Geol. Soc. Am. Bull.*, *110*, 779–800.

Bohannon, R. G., and T. Parsons (1995), Tectonic implications of post-30 Ma Pacific and North American relative plate motions, *Geol. Soc. Am. Bull.*, *107*, 937–959.

Brabb, E. E., J. C. Clark, and C. B. Throckmorton (1977), Measured sections of Paleogene rocks from the California Coast Ranges, *U.S. Geol. Surv. Open File Rep.*, *77-714*, 114 pp.

Brocher, T. M., U. S. ten Brink, and T. Abramovitz (1999), Synthesis of crustal seismic structure and implications for the concept of a slab gap beneath coastal California, *Int. Geol. Rev.*, *41*, 263–274.

Burnham, K. (1998), Preliminary comparison and correlation of two Cretaceous conglomerates, the strata of Anchor Bay and an unnamed unit in the Pilarcitos block, across the San Gregorio and San Andreas faults, in *Geology and Tectonics of the Gualala Block, Northern California, Book 84*, edited by W. P. Elder, pp. 95–119, Pac. Sect., Soc. for Sediment. Geol., Walnut, Calif.

Cande, S. C., and D. V. Kent (1995), Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6095.

Cande, S. C., C. A. Raymond, J. M. Stock, and W. F. Haxby (1995), Geophysics of the Pitman fracture zone and Pacific-Antarctic Plate motions during the Cenozoic, *Science*, *270*, 947–953.

Cande, S. C., J. M. Stock, R. D. Mueller, and T. Ishihara (2000), Cenozoic motion between East and West Antarctica, *Nature*, *404*, 145–150.

Chu, D., and R. G. Gordon (1999), Evidence for motion between Nubia and Somalia along the Southwest Indian Ridge, *Nature*, *398*, 64–66.

Clark, J. C. (1981), Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges, *U.S. Geol. Surv. Prof. Pap.*, *1168*, 51 pp.

Clark, J. C., E. E. Brabb, H. G. Greene, and D. C. Ross (1984), Geology of Point Reyes Peninsula and implications for San Gregorio fault history, in *Tectonics and Sedimentation Along the California Margin*, edited by J. K. Crouch and S. B. Bachman, pp. 67–86, Pac. Sect., Soc. for Sediment. Geol., Walnut, Calif.

Cole, R. B., and A. R. Basu (1992), Middle Tertiary volcanism during ridge-trench interactions in western California, *Science*, *258*, 793–796.

Cole, R. B., and A. R. Basu (1995), Nd-Sr isotope geochemistry and tectonics of ridge subduction and middle Cenozoic volcanism in western California, *Geol. Soc. Am. Bull.*, *107*, 167–179.

Cole, R. B., and R. G. Stanley (1995), Middle Tertiary extension recorded by lacustrine fan–delta deposits, Plush Ranch basin, western Transverse Ranges, California, *J. Sediment. Res., Sect. B*, *65*, 455–468.

Cole, R. B., and R. G. Stanley (1998), Volcanic rocks of the Santa Maria province, California, *U.S. Geol. Surv. Bull.*, *1995-R*, R1–R35.

Crouch, J. K., and J. Suppe (1993), Late Cenozoic tectonic evolution of the Los Angles basin and inner California borderland: A model for core complex-like crustal extension, *Geol. Soc. Am. Bull.*, *105*, 1415–1434.

Crowell, J. C. (1962), Displacement along the San Andreas fault, California, *Spec. Pap. Geol. Soc. Am.*, *71*, 61 pp.

Crowell, J. C. (1973), Problems concerning the San Andreas fault system in southern California, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, edited by R. L. Kovach and A. Nur, *Stanford Univ. Publ. Geol. Sci.*, *13*, 125–135.

Crowell, J. C. (1974), Origin of late Cenozoic basins in southern California, in *Tectonics and Sedimentation*, edited by W. R. Dickinson, *Spec. Publ. Soc. Econ. Paleontol. Mineral.*, *22*, 190–204.

Crowell, J. C. (1987), Late Cenozoic basins of onshore southern California—Complexity is the hallmark of their tectonic history, in *Cenozoic Basin Development of Coastal California, Rubey Volume VI*, edited by R. V. Ingersoll and W. G. Ernst, pp. 207–241, Prentice-Hall, Upper Saddle River, N. J.

Dalrymple, G. B. (1979), Critical tables for conversion of K-Ar ages from old to new constants, *Geology*, *7*, 558–560.

Davisson, C. M., R. D. Law, and K. A. Eriksson (1992), Asymmetric geometry of a half-graben basin as indicated be sediment character: An example from the Diligencia basin, southeastern California, *Geol. Soc. Am. Abstr. Programs*, *24*, A52.

Dickinson, W. R. (1996), Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system, *Special Paper Geol. Soc. Am.*, *305*, 46 pp.

Dickinson, W. R. (1997), Tectonic implications of Cenozoic volcanism in coastal California, *Geol. Soc. Am. Bull.*, *109*, 936–954.

Dickinson, W. R., R. A. Armin, N. Beckvar, T. C. Goodin, S. U. Janecke, R. A. Mark, R. D. Norris, G. Radel, and A. A. Wortman (1987), Geohistory analysis of rates of sediment accumulation and subsidence for selected California basins, in *Cenozoic Basin Development of Coastal California, Rubey Volume VI*, edited by R. V. Ingersoll and W. G. Ernst, pp. 1–23, Prentice-Hall, Upper Saddle River, N. J.

Dillon, J. T., and P. L. Ehlig (1993), Displacement on the southern San Andreas fault, in *The San Andreas Fault System—Displacement, Palinspastic Reconstruction, and Geologic Evolution*, edited by R. E. Powell, R. J. Weldon II, and J. C. Matti, *Mem. Geol. Soc. Am.*, *178*, 199–216.

Dunkel, C. A. (1997), Año Nuevo Basin, in *1995 National Assessment of United States Oil and Gas Resources Assessment of the Pacific Outer Continental Shelf Region*, *OCS Rep. MMS 97-0019*, edited by C. A. Dunkel and K. A. Piper, pp. 75–83, Miner. Manage. Serv., Camarillo, Calif.

Eaton, G. P. (1957), Miocene Volcanic Activity in the Los Angeles Basin and vicinity, Ph.D. thesis, 388 pp., Calif. Inst. of Technol., Pasadena.

Fernandez, L. S., and R. N. Hey (1991), Late Tertiary tectonic evolution of the seafloor spreading system off the coast of California between the Mendocino and Murray fracture zones, *J. Geophys. Res.*, *96*, 17,955–17,979.

Fletcher, J. M. (2003), Tectonic restoration of the Baja California microplate and the geodynamic evolution of the Pacific–North American plate margin, *Geol. Soc. Am. Abstr. Programs*, *35*(4), 9.

Fox, K. F., Jr., R. J. Fleck, G. H. Curtis, and C. E. Meyer (1985), Implications of the northwesterly younger age of the volcanic rocks of west-central California Coast Ranges, *Geol. Soc. Am. Bull.*, *96*, 647–654.

Fritsche, A. E., and G. D. Thomas (1990), New early Miocene K-Ar date for basalt in the Hurricane Deck Formation, central Santa Barbara County, California, *Geol. Soc. Am. Abstr. Programs*, *22*, 23–24.

Frizzell, V. A., Jr., and P. W. Weigand (1993), Whole-rock K-Ar ages and geochemical data from middle Cenozoic volcanic rocks, southern California—A test of correlations across the San Andreas fault, in *The San Andreas Fault System—Displacement, Palinspastic Reconstruction, and Geologic Evolution*, edited by R. E. Powell, R. J. Weldon II, and J. C. Matti, *Mem. Geol. Soc. Am.*, *178*, 273–287.

Gans, P. B. (1997), Large-magnitude Oligo-Miocene extension in southern Sonora: Implication for the tectonic evolution of northwest Mexico, *Tectonics*, *16*, 388–408.

Gans, P. B., G. A. Mahood, and E. R. Schermer (1989), Synextensional magmatism in the Basin and Range province: A case study from the eastern Great Basin, *Spec. Pap. Geol. Soc. Am.*, *233*, 53 pp.

Gastil, R. G., D. Krummenacher, and J. A. Minch (1979), The record of Cenozoic volcanism around the Gulf of California, part I, *Geol. Soc. Am. Bull.*, *90*, 839–857.

Gill, J. B. (1981), *Orogenic Andesites and Plate Tectonics*, 401 pp., Springer, New York.

Goodman, E. D., and P. E. Malin (1992), Evolution of the southern San Joaquin basin and mid-Tertiary ''transitional'' tectonics, central California, *Tectonics*, *11*, 478–498.

Gorring, M. L., S. M. Kay, P. K. Zeitler, V. A. Ramos, D. Rubiolo, M. L. Fernandez, and J. L. Panza (1997), Neogene Patagonian plateau lavas: Continental magmas associated with ridge collision at the Chile triple junction, *Tectonics*, *16*, 1–17.

Graham, S. A. (1978), The role of the Salinian block in evolution of San Andreas fault system, California, *Am. Assoc. Pet. Geol. Bull.*, *62*, 2214–2231.

Graham, S. A., R. G. Stanley, J. V. Bent, and J. B. Carter (1989), Oligocene and Miocene paleogeography of central California and offset along the San Andreas fault, *Geol. Soc. Am. Bull.*, *101*, 711–730.

Hall, C. A., Jr. (1981), San Luis Obispo transform fault and middle Miocene rotation of the western Transverse Ranges, California, *J. Geophys. Res.*, *86*, 1015–1031.

Handschumacher, D. W. (1976), Post-Eocene plate tectonics of the eastern Pacific, in *The Geophysics of the Pacific Ocean Basin and Its Margin*, *Geophys. Monogr. Ser.*, vol. 19, edited by G. H. Sutton, M. H. Manghnani, and R. Moberly, pp. 177–202, AGU, Washington, D. C.

Hendrix, E. P., and R. V. Ingersoll (1987), Tectonics and alluvial sedimentation of the upper Oligocene/lower Miocene Vasquez Formation, Soledad basin, southern California, *Geol. Soc. Am. Bull.*, *98*, 647–663.

Henry, C. D., and J. J. Aranda-Gomez (2000), Plate interactions control middle-late Miocene, proto-Gulf and Basin and Range extension in the southern Basin and Range, *Tectonophysics*, *318*, 1–26.

Hole, M. J., and R. D. Larter (1993), Trench-proximal volcanism following ridge crest-trench collision along the Antarctic peninsula, *Tectonics*, *12*, 897–910.

Hurst, R. W. (1982), Petrogenesis of the Conejo volcanic suite, southern California: Evidence for mid-ocean ridge-continental margin interactions, *Geology*, *27*, 593–596.

Ingersoll, R. V., and P. E. Rumelhart (1999), Three-stage evolution of the Los Angeles basin, southern California, *Geology*, *27*, 593–596.

Ingle, J. C., Jr. (1980), Cenozoic paleobathymetry and depositional history of selected sequences within the southern California Continental Borderland, *Spec. Publ. Cushman Found. Foraminiferal Res.*, *19*, 163–195.

Jachens, R. C., C. M. Wentworth, and R. J. McLaughlin (1998), Pre-San Andreas location of the Gualala block inferred from magnetic and gravity anomalies, in *Geology and Tectonics of the Gualala Block, Northern California, Book 84*, edited by W. P. Elder, pp. 27–64, Pac. Sect., Soc. for Sediment. Geol., Walnut, Calif.

Johnson, C. M., and J. R. O'Neil (1984), Triple junction magmatism—A geochemical study of Neogene volcanic rocks in western California, *Earth Planet. Sci. Lett.*, *71*, 241–262.

Klitgord, K. D., and H. S. Schouten (1986), Plate kinematics of the central Atlantic, in *The Geology of North America*, vol. M, *The Western North Atlantic Region*, edited by P. R. Vogt and B. E. Tucholke, pp. 351–378, Geol. Soc. of Am., Boulder, Colo.

Lachenbruch, A. H., and J. H. Sass (1980), Heat flow and energetics of the San Andreas fault zone, *J. Geophys. Res.*, *85*, 6185–6223.

Lagoe, M. B. (1987a), Middle Cenozoic unconformity-bounded stratigraphic units in the Cuyama and southern San Joaquin basins, California: Record of eustatic and tectonic events in active margin basins, in *Timing and Depositional History of Eustatic Sequences: Constraints on Seismic Stratigraphy*, edited by C. A. Ross and D. Haman, *Spec. Publ. Cushman Found. Foraminiferal Res.*, *24*, 15–32.

Lagoe, M. B. (1987b), Cenozoic basin development, Cuyama basin, California, in *Cenozoic Basin Development of Coastal California, Rubey Volume VI*, edited by R. V. Ingersoll and W. G. Ernst, pp. 172–206, Prentice-Hall, Upper Saddle River, N. J.

Lemaux, J., II (2000), The motion between Nubia and Somalia from magnetic anomaly and fracture zone crossings flanking the Southwest Indian Ridge, M.S. thesis, 146 pp., Rice Univ., Houston, Tex.

Lemaux, J., II, R. G. Gordon, and J.-Y. Royer (2002), Location of the Nubia-Somalia boundary along the Southwest Indian Ridge, *Geology*, *30*(4), 339–342.

Lonsdale, P. (1991), Structural patterns of the Pacific floor offshore of peninsular California, in *The Gulf and Peninsular Province of the Californias*, edited by J. P. Dauphin and B. R. T. Simoneit, *Mem. AAPG*, *47*, 87–125.

Loomis, K. B., and J. C. Ingle Jr. (1994), Subsidence and uplift of the Late Cretaceous-Cenozoic margin of California: New evidence from the Gualala and Point Arena basins, *Geol. Soc. Am. Bull.*, *106*, 915–931.

Luyendyk, B. P. (1991), A model for Neogene crustal rotations, transtension, and transpression in southern California, *Geol. Soc. Am. Bull.*, *103*, 1528–1536.

Luyendyk, B. P., and J. S. Hornafius (1987), Neogene crustal rotations, fault slip, and basin development in southern California, in *Cenozoic Basin Development of Coastal California, Rubey Volume VI*, edited by R. V. Ingersoll and W. G. Ernst, pp. 259–283, Prentice-Hall, Englewood Cliffs, Upper Saddle River, N. J.

Luyendyk, B. P., M. J. Kamerling, R. R. Terres, and J. S. Hornafius (1985), Simple shear of southern California Neogene time suggested by paleomagnetic declinations, *J. Geophys. Res.*, *90*, 12,455–12,466.

Luyendyk, B. P., P. B. Gans, and M. J. Kamerling (1998), $^{40}Ar/^{39}Ar$ geochronology of southern California Neogene volcanism, in *Contributions to the Geology of the Northern Channel Islands, Southern California*, vol. MP-45, edited by P. W. Weigand, pp. 9–35, Pac. Sect., Am. Assoc. of Pet. Geol., Bakersfield, Calif.

Mankinen, E. A. (1972), Paleomagnetism and potassium-argon ages of the Sonoma Volcanics, California, *Geol. Soc. Am. Bull.*, *83*, 2063–2072.

Matthews, V., III (1973), Geology of the Pinnacles Volcanic Formation and the Neenach Volcanic Formation and their bearing on the San Andreas fault problem, Ph.D. dissertation, 214 pp., Univ. of Calif., Santa Cruz.

Matthews, V., III (1976), Correlation of Pinnacles and Neenach volcanic formations and their bearing on San Andreas fault problem, *Am. Assoc. Pet. Geol. Bull.*, *60*, 2128–2141.

May, D. J., and N. W. Walker (1989), Late Cretaceous juxtaposition of metamorphic terranes in the southeastern San Gabriel Mountains, California, *Geol. Soc. Am. Bull.*, *101*, 1246–1267.

Mayer, L. (1991), Central Los Angeles basin—Subsidence and thermal implications for tectonic evolution, in *Active Margin Basins*, edited by K. T. Biddle, *Mem. AAPG*, *52*, 185–195.

McCrory, P. A., D. S. Wilson, J. C. Ingle Jr., and R. G. Stanley (1995), Neogene geohistory analysis of Santa Maria basin, California and its relationship to transfer of central California to the Pacific plate, *U.S. Geol. Surv. Bull.*, *1995-J*, J1–J38.

McCulloch, D. S. (1989), Evolution of the offshore central California margin, in *The Geology of North America*, vol. N, *The Eastern Pacific Ocean and Hawaii*, edited by E. L. Winterer, D. M. Hussong, and R. W. Decker, pp. 439–470, Geol. Soc. of Am., Boulder, Colo.

McIntosh, W. C., J. W. Geissman, C. E. Chapin, M. J. Kunk, and C. D. Henry (1992), Calibration of the latest Eocene-Oligocene geomagnetic polarity time scale using $^{40}Ar/^{39}Ar$ dated ignimbrites, *Geology*, *20*, 459–463.

McLaughlin, R. J., W. V. Sliter, D. H. Sorg, P. C. Russell, and A. M. Sarna-Wojcicki (1996), Large-scale right-slip displacement on the east San Francisco Bay region fault system, California: Implication for location of late Miocene to Pliocene Pacific plate boundary, *Tectonics*, *15*, 1–18.

McLean, H. (1994), Geologic map of the Lopez Mountain quadrangle, San Luis Obispo County, California, *U.S. Geol. Surv. Geol. Quad. Map, GQ-1723*.

McLean, H. (1995), Geologic map of the Tar Spring Ridge quadrangle, San Luis Obispo County, California, *U.S. Geol. Surv. Misc. Field Stud. Map, MF-2298*.

Menard, H. W. (1978), Fragmentation of the Farallon plate by pivoting subduction, *J. Geol.*, *86*, 99–110.

Miller, K. C., J. M. Howie, and S. D. Ruppert (1992), Shortening within underplated oceanic crust beneath the central California margin, *J. Geophys. Res.*, *97*, 19,961–19,980.

Naar, D. F., and R. N. Hey (1991), Tectonic evolution of the Easter Microplate, *J. Geophys. Res.*, *96*, 7961–7993.

Nakata, J. K., et al. (1993), New radiometric ages and tephra correlations from the San Jose and the northeastern part of the Monterey 1:100,000 map quadrangles, California, *Isochron West*, 19–32.

Nicholson, C., C. C. Sorlien, and B. P. Luyendyk (1992), Deep structure and tectonics in the offshore southern Santa Maria Basin, California, *Geology*, *20*, 239–242.

Nicholson, C., C. C. Sorlien, T. M. Atwater, J. C. Crowell, and B. P. Luyendyk (1994), Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system, *Geology*, *22*, 491–495.

Nilsen, T. H. (1987), Stratigraphy and sedimentology of the Eocene Tejon Formation, western Tehachapi and San Emigdio Mountains, California, *U.S. Geol. Surv. Prof. Pap.*, *1768*, 110 pp.

Norton, I. O. (1995), Plate motions in the North Pacific: The 43 Ma nonevent, *Tectonics*, *14*, 1080–1094.

Nourse, J. A., T. H. Anderson, and L. T. Silver (1994), Tertiary metamorphic core complexes in Sonora, northwestern Mexico, *Tectonics*, *13*, 359–366.

Nourse, J. A., T. H. Anderson, and L. T. Silver (1998), Igneous and tectonic response of the eastern San Gabriel Mountains to Neogene extension and rotation of the Transverse Ranges block, *94th Annu. Meet. Guideb. Field Trip 10*, 15 pp., Cordilleran Sect., Geol. Soc. of Am., Long Beach, Calif.

Oskin, M., and J. Stock (2003), Pacific-North America plate motion and opening of the Upper Delfin Basin, northern Gulf of California, Mexico, *Geol. Soc. Amer. Bull.*, *115*, 1173–1190.

Oskin, M., J. M. Stock, and A. Martin-Barajas (2001), Rapid localization of Pacific–North America plate motion on the Gulf of California, *Geology*, *21*, 459–462.

Page, B. M., and T. M. Brocher (1993), Thrusting of the central California margin over the edge of the Pacific plate during the transform regime, *Geology*, *21*, 635–638.

Pardo-Casas, F., and P. Molnar (1987), Relative motion for the Nazca (Farallon) and South American plates since Late Cretaceous time, *Tectonics*, *6*, 233–248.

Plescia, J. B., G. J. Calderone, and L. W. Snee (1994), Paleomagnetic analysis of Miocene basalt flows in the Tehachapi Mountains, California, *U.S. Geol. Surv. Bull.*, *2100*, 11 pp.

Royer, J.-Y., and T. Chang (1991), Evidence for relative motions between the Indian and Australian plates during the last 20 m.y. from plate tectonic reconstructions: Implications for the deformation of the Indo-Australian plate, *J. Geophys. Res.*, *96*, 11,779–11,802.

Rusby, R. I., and R. C. Searle (1995), A history of the Easter microplate, 5.25 Ma to present, *J. Geophys. Res.*, *100*, 12,617–12,640.

Schouten, H., K. D. Klitgord, and D. G. Gallo (1993), Roller bearing microplate kinematics, *J. Geophys. Res.*, *98*, 6689–6701.

Sedlock, R. L., and D. H. Hamilton (1991), Late Cenozoic tectonic evolution of southwestern California, *J. Geophys. Res.*, *96*, 2325–2351.
Seiders, V. M. (1982), Geologic map of an area near York Mountain, San Luis Obispo County, California, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I–1369*.
Shackleton, N. J., M. A. Hall, I. Raffi, L. Tauxe, and J. C. Zachos (2000), Astronomical calibration age for the Oligocene-Miocene boundary, *Geology*, *28*, 447–450.
Sharma, M. B. A. R., R. B. Cole, and P. G. DeCelles (1991), Basalt-rhyolite volcanism by MORB-continental crust interaction: Nd, Sr-isotopic and geochemical evidence from southern San Joaquin basin, California, *Contrib. Mineral. Petrol.*, *109*, 159–172.
Sims, J. D. (1993), Chronology of displacement on the San Andreas fault in Central California: Evidence from reversed positions of exotic rock bodies near Parkfield, California, in *The San Andreas Fault System: Displacement, Palinspastic Reconstruction, and Geologic Evolution*, edited by R. E. Powell, R. J. Weldon II, and J. C. Matti, *Mem. Geol. Soc. Am.*, *178*, 231–256.
Snow, J. K., and B. P. Wernicke (2000), Cenozoic tectonism in the central Basin and Range; magnitude, rate, and distribution of upper crustal strain, *Am. J. Sci.*, *300*, 659–719.
Spencer, J. E., and W. R. Normark (1979), Tosco-Abreojos fault zone: A Neogene transform plate boundary within the Pacific margin of southern Baja California, *Geology*, *7*, 554–557.
Spittler, T. E., and M. A. Arthur (1982), The lower Miocene Diligencia Formation of the Orocopia Mts., southern California: Stratigraphy, petrology, sedimentology, and structure, in *Cenozoic Nonmarine Deposits of California and Arizona*, edited by R. V. Ingersoll and M. O. Woodburne, pp. 83–99, Pac. Sect., Soc. for Sediment. Geol., Walnut Creek, Calif.
Stakes, D. S., R. W. Kistler, and D. E. Champion (1998), Isotopic and field characteristics of Salinian granites from the Monterey Bay, *Eos Trans. AGU*, *79*(45), Fall Meet. Suppl., F824.
Stanley, R. G. (1985), Middle Tertiary sedimentation and tectonics of the La Honda basin, central California, *U.S. Geol. Surv. Open File Rep., 85-596*, 263 pp.
Stanley, R. G. (1987), Implications of the northwestwardly younger age of the volcanic rocks of west-central California—Alternative interpretation, *Geol. Soc. Am. Bull.*, *98*, 612–614.
Stanley, R. G. (1988), Late Oligocene and early Miocene volcanism, faulting, and sedimentation in west-central California, *AAPG Bull.*, *72*, 396.
Stanley, R. G. (1990), Evolution of the Tertiary La Honda basin, central California, in *Geology and Tectonics of the Central California Coast Region, San Francisco to Monterey, Volume and Guidebook*, vol. GB67, edited by H. G. Greene et al., pp. 1–29, Pac. Sect., Am. Assoc. of Pet. Geol., Bakersfield, Calif.
Stanley, R. G., M. L. Cotton, D. Bukry, M. V. Filewicz, Z. C. Valin, and D. R. Vork (1994), Stratigraphic revelations regarding the Rincon Shale (lower Miocene) in the Santa Barbara coastal area, California, *AAPG Bull.*, *78*, 675–676.
Stanley, R. G., S. Y. Johnson, C. C. Swisher III, M. A. Mason, J. D. Obradovich, M. L. Cotton, M. V. Filewicz, and D. R. Vork (1996), Age of the Lospe Formation (early Miocene) and origin of the Santa Maria basin, California, *U.S. Geol. Surv. Bull.*, *1995-M*, M1–M37.
Stanley, R. G., D. S. Wilson, and P. A. McCrory (2000), Locations and ages of middle Tertiary volcanic centers in coastal California, *U.S. Geol. Surv. Open File Rep., 00-154*, 27 pp.
Steckler, M. S., and A. B. Watts (1978), Subsidence of the Atlantic-type continental margin off New York, *Earth Planet. Sci. Lett.*, *41*, 1–13.
Stock, J. M., and K. V. Hodges (1989), Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific plate, *Tectonics*, *8*, 99–115.
Stock, J. M., and P. Molnar (1988), Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates, *Tectonics*, *7*, 1339–1384.
Taylor, F. E. (1988), The geology of middle Tertiary rocks at Pescadero State Beach and Point Año Nuevo, M.S. thesis, 188 pp., Calif. State Univ., Fresno.
Taylor, F. E. (1990), Syndepositional magmatism within the Vaqueros(?) Formation (upper Oligocene–lower Miocene) of Pescadero State Beach and Punta Año Nuevo, San Mateo County, California, in *Geology and Tectonics of the Central California Coast Region, San Francisco to Monterey, Volume and Guidebook*, vol. GB67, edited by R. E. Garrison et al., pp. 57–70, Pac. Sect., Am. Assoc. of Pet., Bakersfield, Calif.
ten Brink, U. S., N. Shimizu, and P. C. Molzer (1999), Plate deformation at depth under northern California: Slab gap or stretched slab?, *Tectonics*, *18*, 1084–1098.
Tennyson, M. E. (1989), Pre-transform early Miocene extension in western California, *Geology*, *17*, 792–796.
Tréhu, A. M. (1991), Tracing the subducted oceanic crust beneath the central California continental margin: Results from ocean bottom seismometers deployed during the 1986 Pacific Gas and Electric EDGE experiment, *J. Geophys. Res.*, *96*, 6493–6505.
Turner, D. L. (1968), Potassium-argon dates concerning the Tertiary foraminiferal time scale and San Andreas fault displacement, Ph.D. thesis, 99 pp., Univ. of Calif., Berkeley.
Turner, D. L. (1970), Potassium-argon dating of Pacific Coast Miocene foraminiferal stages, in *Radiometric Dating and Paleontologic Zonation*, edited by O. L. Bandy, *Spec. Pap. Geol. Soc. Am.*, *124*, 91–129.
Turner, D. L., and R. H. Campbell (1979), Age of the Conejo Volcanics, *U.S. Geol. Surv. Bull.*, *1457-E*, 18–22.
Underwood, M. B., and M. M. Laughland (2001), Paleothermal structure of the Point San Luis slab of central California: Effects of Late Cretaceous underplating, out-of-sequence thrusting, and late Cenozoic dextral offset, *Tectonics*, *20*, 97–111.
Underwood, M. B., M. M. Laughland, K. L. Shelton, and R. L. Sedlock (1995), Thermal maturity trends within Franciscan rocks near Big Sur, California: Implications for offset along the San Gregorio-San Simeon-Hosgri fault zone, *Geology*, *23*, 839–842.
van Hinte, J. E. (1978), Geohistory analysis—Application of micropaleontology in exploration geology, *AAPG Bull.*, *62*, 201–222.
Vedder, J. G., H. McLean, and R. G. Stanley (1991), Paleogeographic implications of an erosional remnant of Paleogene rocks southwest of the Sur-Nacimiento fault zone, southern Coast Ranges, California, *Geol. Soc. Am. Bull.*, *103*, 941–952.
Vedder, J. G., H. McLean, and R. G. Stanley (1994), New 1:24,000-scale geologic maps show stratigraphic and structural relations that require reinterpretation of Cretaceous and Cenozoic tectonic events in the Sierra Madre–San Rafael Mountains area, California, *Geol. Soc. Am. Abstr. Programs*, *26*, 100–101.
Wakabayashi, J. (1999), Distribution of displacement on and evolution of a young transform fault system: The northern San Andreas fault system, California, *Tectonics*, *18*, 1245–1274.
Webster, F., D. J. Burdick, and K. A. Yenne (1988), Central California planning area geologic report, *OCS Rep. MMS 88-0081*, 79 pp., Miner. Manage. Serv., Los Angeles, Calif.
Weigand, P. W., and K. L. Savage (1993), Review of the petrology and geochemistry of the Miocene Conejo Volcanics of the Santa Monica Mountains, California, in *Depositional and Volcanic Environments of Middle Tertiary Rocks in the Santa Monica Mountains, Southern California, Book 72*, edited by P. W. Weigand, A. E. Fritsche, and G. E. Davis, pp. 93–112, Pac. Sect., Soc. for Sediment. Geol., Walnut Creek, Calif.
Weigand, P. W., and C. C. Swisher III (1991), Are the Neenach and Pinnacles Volcanic Formations miscorrelated? New evidence from $^{40}Ar/^{39}Ar$ dating, *Eos Trans. AGU*, *72*(44), Fall Meet. Suppl., 577.
Weigand, P. W., and J. M. Thomas (1990), Middle Cenozoic volcanic fields adjacent to the San Andreas fault, central California—Correlation and petrogenesis, in *San Andreas Fault—Cajon Pass to Wallace Creek*, *South Coast Geol. Soc. Guideb.*, vol. 17, vol. 1, edited by E. J. Baldwin et al., pp. 207–222, South Coast Geol. Soc., Santa Ana, Calif.
Weigand, P. W., K. L. Savage, T. Reid, and B. D. Chinn (1998), Composition of volcanic rocks on Santa Rosa, San Miguel, and Santa Barbara Islands, California, in *Contributions to the Geology of the Northern Channel Islands, Southern California*, vol. MP-45, edited by P. W. Weigand, pp. 37–47, Am. Assoc. Pet. Geol., Pac. Sect., Bakersfield.
Wentworth, C. M., D. L. Jones, and E. E. Brabb (1998), Geology and regional correlation of the Cretaceous and Paleogene rocks of the Gualala Block, California, in *Geology and Tectonics of the Gualala Block, Northern California, Book 84*, edited by W. P. Elder, pp. 3–26, Pac. Sect., Soc. for Sediment. Geol., Walnut Creek, Calif.
Wernicke, B. P., and J. K. Snow (1998), Cenozoic tectonism in the central Basin and Range: Motion of the Sierran-Great Valley block, *Int. Geol. Rev.*, *40*, 403–410.
Wernicke, B. P., G. J. Axen, and J. K. Snow (1988), Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada, *Geol. Soc. Am. Bull.*, *100*, 1738–1757.
West, J. C., T. W. Redin, G. C. Manings, W. A. Bartling, and K. E. Green (1988), Correlation section across Los Angeles basin from Palos Verdes Hills to San Gabriel Mountains, *Correlation Section CS 3R*, Am. Assoc. of Pet. Geol., Pac. Sect., Los Angeles, Calif.
Wilson, D. S. (1988), Tectonic history of the Juan de Fuca Ridge over the last 40 million years, *J. Geophys. Res.*, *93*, 11,863–11,876.
Wilson, D. S. (1996), Fastest known spreading on the Miocene Cocos-Pacific plate boundary, *Geophys. Res. Lett.*, *23*, 3003–3006.
Wright, T. L. (1991), Structural geology and tectonic evolution of the Los Angeles basin, in *Active Margin Basins*, edited by K. T. Biddle, *AAPG Mem.*, *52*, 35–134.
Zandt, G., and K. R. Furlong (1982), Evolution and thickness of the lithosphere beneath coastal California, *Geology*, *10*, 376–381.

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